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ABSTRACT

This paper reports on the learning of difficult and complex concepts, the characteristics of these concepts that make them difficult for students to learn and understand well, the kinds of misconceptions students acquire, and the difficulty of changing these mistaken beliefs. A scheme, the Conceptual Stability Scheme, is presented for analyzing a concept and its related concepts for potential stability. A set of studies is reviewed that confirmed that the misconception that was predicted to be highly stable according to the Conceptual Stability Scheme was, in fact, highly stable. The mental maneuvers (knowledge shields) learners engage in to ward off changing their beliefs are presented and discussed. Many different kinds of shields are used in a variety of circumstances. (Contains 23 figures and 48 references.) (Author/SLD)

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Conceptual Understanding and Stability, and Knowledge Shields for Fending Off Conceptual Change

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Conceptual Understanding and Stability, and Knowledge Shields for Fending Off Conceptual Change

[Final Report, 1994, Office of Naval Research, Cognitive Science Division,
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This report is about the learning of scientific (in particular, biological/biomedical) concepts, the strongly held misunderstandings that can develop in this learning, and the difficulty of changing these misconceptions once they are acquired. Most importantly, the paper is about ways of thinking and learning that lead to misconception and the kinds of mental operations learners utilize in order to avoid having to change erroneous beliefs; that is, it is about the mental maneuvers people engage to ward off "changing their minds," even when such change would lead to better understanding. Before starting into a discussion of these topics, it is useful to provide a bit of background about the program of research from which the findings presented were discovered.

This pertinent background is presented in the first main section. In the second main section, an analytic scheme, the Conceptual Stability Scheme, is presented. This is a scheme that can be applied to a concept and its set of associated concepts to predict how prone the cluster will be to misconception among learners, and how stably (pervasively, robustly, and with constantly over time) held these misconceptions will be once they are learned. In this same section, the Conceptual Stability Scheme is then applied in detail to a set of important physiological concepts about the cardiovascular system, and predictions are made about the stability of their associated misconceptions In the third main section, a set of experimental studies is reported that were designed to test the predictions of stability that were made according to the Conceptual Stability Scheme for the cardiovascular misconceptions discussed in the second section. These studies include an "instructional"/challenge study, in which directed challenges were made to these misconceptions, in an attempt to rectify them. This is followed, in the fourth main section, by the presentation and discussion of a number of mental operations, what we have called Knowledge Shields, that subjects used to rationalize affronts to their faulty beliefs, to avoid having to change these beliefs. A summary, and some conclusions and implications are presented in the last main section of the report.

BACKGROUND AND INTRODUCTION

The program of research was begun in about 1983 with the initial goal of coming to understand better the role of (especially, complex and difficult) basic biomedical conceptual knowledge in the clinical reasoning and performance of the medical physician. To that time there had been little empirical investigation of this, and there has still been little (but see, for example, Lesgold, Rubinson, Feltovich, Glaser, Klopfer, & Wang, 1988; Feltovich, Coulson, Spiro, & Dawson-Saunders, 1992; Patel, Evans, & Groen, 1989). What had already been done in research, and most of what has been done since, looked at the clinical reasoning of the physician and attempted to trace back from this intact reasoning to possible bases for it in conceptual knowledge. The primary finding from this kind of approach has been that little linkage has been seen, or at least that such dependencies and influences are quite difficult to detect. This can be either because there is little connection or because such connection is well hidden, since it is known that with extended use knowledge is transformed, often in the direction of increased covertness, and lessened availability to conscious awareness and inspection (e.g., Feltovich, Johnson, Moller, & Swanson, 1984; Schmidt & Boshhuizen, 1992; Schneider & Shiffrin, 1977).

This suggested for the authors a different approach to studying basic science knowledge in clinical reasoning: this was to study from the beginning of their education, medical students' learning and understanding of biomedical topics, and to learn how they understood and misunderstood these. Armed with this kind of knowledge, we speculated that it would then be possible to trace out into clinical practice, that is, to people working with medical clinical cases of illness, the effects such understanding, or especially misunderstanding, might have on clinical thinking and action. This was not a common idea at the time, although, as time has passed, parts of the scheme have been adopted by others (e.g., Patel, Kaufman, & Magder, 1991).

Studying, in depth, students' understanding of concepts from biomedical science placed a high premium on the judiciousness with which the concepts were chosen for study. Such study is complicated and time consuming; hence, it was important to focus on concepts of great potential importance, lest findings from the research be dismissed as superfluous or the potential ties to clinical reasoning be minimal, at best. To help ensure the importance of what was chosen for study, a survey was conducted of teachers from all medical schools in the United States and Canada, who were asked to identify biomedical science concepts both important to practicing medicine and difficult for students to learn and apply well (Dawson-Saunders, Feltovich, Coulson, & Steward, 1990). Students' learning of concepts identified in this survey has been investigated by the authors (e.g., Myers, Feltovich, Coulson, Adami, & Spiro, 1990; this report) and others (e.g., Patel et al., 1991). This survey used to identify concepts has been noted in order to emphasize that the concepts addressed in this report are not just academic; rather, they are viewed by the leaders of medicine as being particularly significant, albeit difficult.

The overall goals of the research have been straightforward, if not easily accomplished. They have been: (1) to determine characteristics of concepts that make them difficult for people to understand and apply in doing tasks, (2) to determine the faulty models and understandings that individuals acquire when learning complex, difficult material, and to determine why these misconceptions are adopted and maintained in belief, (3) to determine characteristics of misconceptions that lead to their being more or less strongly held and resistant to change, (4) to determine in individuals sources of resistance to the adoption of more appropriate beliefs, (5) to feed back from research into the educational setting by designing pedagogical tools that help engender more appropriate and usable understanding (for some of the educational theory and tools that have resulted from this endeavor, see writings regarding Cognitive Flexibility Theory, for example, Feltovich, Spiro, & Coulson, 1993; Spiro, Coulson, Feltovich, and Anderson, 1988; Spiro, Feltovich, Coulson, & Anderson, 1989; Spiro, Feltovich, Jacobson, & Coulson, 1991; Spiro & Yehng, 1991), and finally (and, ironically, now of lesser priority), (6) to trace implications of the learning of basic science, conceptual knowledge out into instances of clinical application where early learnings are likely to have noticeable influences. (Note: Besides conducting this general program of research and development in civilian medicine, the authors have also conducted a similar program, on a smaller scale, within the Navy submarine corpsman medical training program--Feltovich & Coulson, 1992)

A cluster of concepts from cardiovascular physiology and medicine has been the focus of a large part of the authors' investigations. These are concepts that were identified as important and difficult from the survey mentioned earlier, an appraisal that is consistent with the second author's experience in teaching cardiovascular physiology and biophysics. Concepts that have been addressed include (for various discussions of findings from the studies of students' understanding of these concepts the reader may consult, Coulson, Feltovich, & Spiro, 1989; Feltovich, Spiro, & Coulson, 1989, 1993; Spiro et al., 1989): (1) opposition to the flow of blood in the cardiovascular system, also termed cardiovascular impedance, (2) intrinsic regulation of cardiovascular flow, involving the interaction of the Frank-Starling cardiac function relationship and the Guyton vascular function relationship, (3) Cardiac muscle activation and the control of contraction, and (4) cardiac hypertrophy--this last comprising principles underlying growth processes of cardiac muscle in the presence of unusual stress on the muscle.

Although there has been a major focus on cardiovascular concepts, efforts have not been limited to these but have also included studies in the areas of acid-base and electrolyte balance within biomedicine (Myers et al., 1990), literary criticism (Spiro & Yehng, 1990), military strategy (Spiro, Feltovich, Coulson, Jacobson, Durgunoglu, Ravlin, & Jehng. 1990, statistics, law (Feltovich, Spiro, Coulson, & Myers-Kelson, in press), and historical analysis and interpretation (Spiro, Feltovich, Kolar, & Coulson, in preparation).

In all these areas, the authors have been concerned with what we have called "advanced knowledge acquisition," a period between introductory learning and the accomplishment of practiced expertise (e.g., Spiro et al., 1988). This is a period when

students should be in the process of mastering learning materials, not just being introduced to them. We have speculated that problems of learning that occur at the advanced stage have significant bases in the learning and instructional processes of introductory learning, and emerging research is providing support for this claim (e.g., Buckley, 1993).

Misconceptions--Their Nature and Development

In the subject areas the authors have studied, we have found that students display numerous and sometimes strongly held misconceptions (discussions of these are contained in all of our written work, but the reader can consult especially, Feltovich et al. , 1989;1993; Myers et al., 1990; Spiro et al., 1989).

Based on the nature of these misconceptions, a framework or "calculus" of misconception and its development has been developed (Feltovich, 1989; 1993). It addresses some of the sources of misconception, the structure of misconceptions in relation to other knowledge, including other misconceptions, and some cognitive tendencies that abet the contributions to misconception provided from the various sources. With regard to the sources of misconception, there are multiple sources of influence on the development of misunderstandings. Some come from the *instructional process* itself, as when, for instance, complex concepts are overly simplified to provide a starting point for understanding, but where these initial misconceptions remain in more advanced learning or shade this future understanding in a deleterious way. Another harmful influence of the instructional process involves the use of a single representation or analogy that misleads about, or otherwise undermines, fuller understanding of a complex topic (e.g., Spiro, 1989; Zook & DeVesta, 1991). Testing too, as often practiced in schools, contributes to poor understanding by, for example, demanding only the lowest levels of accomplishment (e.g., Feltovich et al., 1993; Fleming & Chambers, 1983; Morgenstern & Renner, 1984). Other influences come from some laboratory practices of *biomedical science*, as when materials and procedures are selected to maximize a laboratory effect, while at the same time eliminating factors necessary for understanding phenomena in real context (Coulson et al., 1989; Wimsatt, 1980). Finally, there appears to be a predilection, at least among many people, to try to simplify complexity, even if inappropriately, in approaching learning and understanding (e.g., Ainley, 1993; Coulson et al., 1989; Dember, 1991; Feltovich et al., 1993; Schommer, 1993). We have referred to this tendency in other papers as the "reductive bias," and it will be taken up again later in this report.

Another facet of the calculus of misconception has to do with the internal structure of misconceptions and their relationships with other misconceptions and with other components of knowledge. Misconceptions (or *any* components of knowledge) do not exist in isolation, but, rather, are highly interrelated among themselves and with other knowledge. In interrelationship, misconceptions can reciprocate so that they bolster each other--believing one misconception can make it easier to believe another, and so forth. Aggregates of faulty knowledge can form misbelief that is stronger and different from the pieces. Misconceptions, like other knowledge, participate in networks of ideas, the overall dynamics and structure of

which can be different from the components: more strongly held and more difficult to predict concerning will happen under perturbation, for example, as the result of attempted instructional remediation (Coulson et al., 1989; Posner, Strike, Hewson, & Gertzog, 1982; Sosa, 1980)

Pervading all dimensions of misconception we have found a substrate of oversimplification, in learning (on the part of the learner), teaching, testing, and sometimes in the basic pursuit of new knowledge through biomedical research. As mentioned, we have named this tendency the reductive bias (the many individual reductive biases that have been identified are presented across a number of papers, in particular, Coulson et al., 1989; Coulson, Feltovich, & Spiro, in press; Feltovich et al., 1989, 1993; Myers et al., 1990; Spiro et al., 1989). In learning and understanding, the reductive bias operates at least three levels of cognition. One is in the *understanding of the subject matter itself* to be learned. Examples are the *similarity bias*, in which concepts that are actually different are taken to be the same, and the *restriction of scope bias*, in which generally applicable principles are believed only to apply in special circumstances. An additional example is that technical terms (such as the term "compliance" in the cardiovascular realm) are interpreted according to their common, everyday meanings (*common connotation bias*). Another level of reduction involves the *mental representation* of material for use in thought. Dynamic processes are represented more statically (*static bias*). Continuous phenomena are represented as discrete (*discreteness bias*). Multidimensional material is represented as uni-dimensional, or in only a very limited number of the relevant dimensions (*reduction of simultaneously considered dimensions*), and so forth. An additional realm of reduction involves fundamental *prefigurative world views* that people hold--epistemological beliefs about the way the world works and is configured. Examples of this level of reductive bias are the presumption that parts always add up to wholes, *insulation from synergism bias* (and that the whole is just the sum of the parts), and that causal relationships are only linear and step-wise, sequential (various kinds of *mechanistic epistemological biases*).

A sample of a student's thinking-aloud protocol from one of our studies is given in Figure 1-A as an example of the application of, and of the effect of application of, a reductive bias in the development of a misconception. In this instance, the reductive bias is the Discreteness Bias (with, perhaps, a bit of the Static Bias--an increased *rate* of flow is treated as an increase in *volume* of flow). The student was first asked to discuss the effect on central venous pressure of increases (or decreases) in cardiac output. In a very discrete, step-wise way, the student traced an increase in blood expelled from the heart from one place, to the next, to the next, until he concluded that there would be a resulting increase in blood, and hence blood pressure, in the veins. He was then, in a later question, asked to discuss the effects of changes in venous pressure on cardiac output. He concluded, correctly, that increases in venous pressure would lead to increased cardiac output. If one couples these two arguments, it is easy to see that the described situation would constitute a positive feedback loop, leading to something like an explosion.

Insert Fig. 1-A about here
(stud. cvp-card output)

STUDENT MODELS OF BLOOD FLOW

CORRECT MODEL: Continuity

STUDENT MODEL: Discontinuity

Examples: Discussing flow regulation

Q: Discuss how cardiac output regulates central venous pressures.

S: Either an increase in heart rate or increase in stroke volume delivers more blood to the arteries, then that blood is delivered to the capillaries, and then flows into the veins, and it goes on to cause more blood to be in the veins. A bigger volume of blood in those structures (veins) would increase pressure, increase central venous pressure...

Q: Discuss how central venous pressures regulate cardiac output.

S: As you increase central venous pressure, you deliver more blood into the atria and, therefore, more blood is um, delivered to the ventricles and more blood is, is, pumped out for a stroke volume.

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Fig.1-A

In this example, a continuous process is understood in a step-wise way, leading to a misconception. The *application of the discreteness bias*, in an attempt to understand a continuous process, leads to the *misconception* that increases in cardiac output lead to increases in venous pressures. In fact, the opposite is true; increases in cardiac output lead to *decreases* in central venous pressure, something more easily appreciated if flow in the cardiovascular system is understood as continuous. Reductive biases are not the same as misconceptions; reductive biases are ways of thinking that contribute to the development of misconceptions when they are applied in efforts at understanding.

Much of what we have discovered about reductive biases can be characterized as follows. It appears that in cognition humans prefer, or are inclined to, *stop dynamics/*change, *break continuity into pieces*, and *put regular or good form* on the resultant. There may be knowledge domains where this kind of thinking is appropriate. However, it leads to misconception and error in domains pervaded by dynamics, continuity, and ill-structuredness. Biology, in particular, is such a domain, and our research has shown misconception in this area of knowledge to be rather common.

In summary of this first major section, important biomedical concepts have been identified in our research program, as have major misconceptions about these important concepts. A "calculus" for characterizing the nature and structure of these and other misconceptions has been created. Prevalent reductive ways of thinking about complex subject matter that contribute to misconception have also been presented. In the next major section, the topic of conceptual stability (e.g., resistance to change of a belief). is taken up, and a scheme of analysis that can be applied to concepts to determine roughly the extent to which they will be stable (e.g., strongly believed and difficult to change) is presented.

A SCHEME FOR DETERMINING THE STABILITY OF MISCONCEPTIONS AND THE DIFFICULTY OF CHANGING THEM.

As has been noted, research in the cognition of science and in science education has revealed that lay people, students, and even those who have undergone the "appropriate" instruction often maintain fundamental misconceptions about important scientific concepts.. Furthermore, misconceptions that have been identified across diverse areas of science can be quite difficult to change; that is, they can be strongly held and intransigent to correction by typical classroom instruction (Champagne, Gunstone, & Klopfer, 1985).

It seems clear that conceptual beliefs and their associated misconceptions will differ in their robustness and their difficulty for changing. For instance, some propositions seem just obviously to differ in their inherent verifiability, the amount and nature of data that would bear on their truth or falsity, their interrelationship with other concepts, and other dimensions that might affect conceptual resiliency--for example, the two propositions "There are 27 windows in that house" versus "My mother is a good woman."

General theories of human belief have been advanced that may shed light on differences in resistance to change among conceptual beliefs (e.g., Pollock, 1979; Sosa, 1980). According to *foundation* theories, belief in a composite of propositions (making up a complex idea) is thought to rest on, and to build in a more or less linear fashion from, one or a small number of critical, "keystone" propositions. Undermining these keystone "props" will cause belief quickly and easily to crumble. In contrast, according to *coherence* theories of belief, belief depends on an intricate system of interlocking, interdependent propositions, no one of which is of sufficient power to undermine (or uphold) the others, and all of which conspire to bolster each other (there has been some suggestion from empirical studies of explanation that coherence in explanation contributes to belief in the truth of the explanation and the strength of this belief, e.g., Patel & Groen,.1992). According to coherence theories, changing belief is a much more complex and difficult matter, since, for instance, the undermining of any component of belief may be overridden by the intermeshed effects of others (cf. Chi, Slotta, & de Leeuw, 1994; Coulson et al., 1989; Feltovich et al., 1989).

One can imagine different scientific (or other areas of subject matter) conceptual structures as conforming more or less well to those espoused by these two theories, with differing implications for their ease of change. Furthermore, empirical studies of conceptual understanding and misconception have differed in their resulting characterizations of conceptual belief and structure, with some claiming these to be constituted of fragmented and labile (unstable, fleeting) components (e.g., diSessa, 1988) and others, including our own, claiming considerably more entrenchment and interwoven, network-like structure (cf. Coulson et al., 1989; Feltovich et al., 1989).

What at first might appear to be controversy can be reconciled by proposing that conceptual beliefs (and associated misconceptions) can *vary* in their nature and degree of entrenchment, from those that are relatively simply structured and easily changeable to those that are complexity structured and highly intransigent. In particular, not all misconceptions are hard to change, *but some are* (including many we have studied, because we have focused in advance on concepts that are supposed to be the most difficult, widely held, and difficult to remedy in a certain knowledge domain--see Dawson-Saunders, Feltovich, Coulson, and Steward, 1990). We have in other places argued that being able to identify misconceptions that are likely to be difficult to change has important implications for instruction. Misconceptions that are likely to be intransigent, of concepts that are themselves particularly important in a body of subject matter (because, for instance, they are especially critical to a wide range of knowledge applications or to the successful understanding of a large number of satellite concepts), are potentially high pay-off targets for special, albeit time and resource consuming, focus in instruction (Feltovich et al., 1992; 1993).

We have adopted the term "stability" to refer to three aspects of conceptual understanding (including misconceptions) that are pertinent: (1) *Pervasiveness* is the extent to which a conceptual belief is held across individuals, (2) *Robustness* is the degree of resistance to change of conceptual belief by challenges posed to it in instruction, and (3) *Constancy* refers the presence of the conceptual belief over time.

It would be highly beneficial to be able to predict, for example, in advance of the design of instruction for a curriculum (and fluidly as the curriculum is being developed and implemented), the important concepts and the conceptual areas that are likely to be the most difficult to understand correctly (and that are likely to lead to misconceptions that are especially hard to emend). Our research group has been working on a scheme for analysis of concepts and their related misconceptions that can help to predict stability in the sense just described. It should be stated that the building of this scheme, the Conceptual Stability Scheme (Feltovich et al., 1993, gives an overview of the Conceptual Stability Scheme), has been iterative, with incarnations of the scheme interspersed with studies from our laboratories to test implications, followed by adjustments to the scheme, followed by further laboratory investigation, and so forth.

The goal for this major section is to present the Conceptual Stability Scheme in some detail. This will be done by showing its instantiation in to a complex biological (and biomedical) concept, opposition to blood flow in the human cardiovascular system (cardiovascular impedance), and the salient related misconceptions that students acquire in learning about this concept.

An overview of the Conceptual Stability Scheme is presented next. (It should be noted that the scheme cannot be applied to a concept in isolation. This is because the understanding and stability of any concept may be highly dependent on numerous other associated concepts, and misconceptions can also be highly intertwined and network-like, e.g., Coulson et al., 1989.) To give a sense of how the scheme is applied to a concept and its set of highly related concepts, selected parts of the scheme are then applied to a group of concepts pertaining to the cardiovascular system. These are ones about which misconceptions are widely held among learners.

Overview of the Scheme for Predicting Conceptual Difficulty and Stability

The scheme for predicting the difficulty of a concept and the stability of misconceptions associated with it has three major parts. The *first* involves the nature of the correct concept to be learned and its set of related concepts. Included, for example, are the difficulty of the individual concepts that are involved in the network of concepts, and how strongly and in what ways members of this group are related to each other. The *second* pertains to characteristics of the network of component misconceptions that make up the overall misconception, that is, to the network of incorrect or faulty interpretations of the correct ideas. Important in this regard is the degree of reciprocation among the members of the network of misconceptions, the degree to which believing one makes it easier to believe others, and vice versa. In general, the higher the overall reciprocation, the greater would be the expected stability (although one can envision exceptions to this--for *extremely* high degrees of reciprocation, for example, the network may come to resemble so much a unity that it does not behave much like a network but, rather, more like a single concept, with robustness against change perhaps reduced). Characteristics of the relationship *between* the correct ideas and the faulty interpretations of them (misconceptions) are also important. For example, because our research has

suggested an inclination in people toward preference and adoption of simple interpretations (Coulson et al., 1989; Feltovich et al., 1989; Spiro et al., 1989) we would predict that misconceptions that are simple of concepts that are actually complex and difficult would be especially stable (cf. Dember, 1991; Zook & DeVesta, 1991). The *third* major factor bearing on stability of a misconception is the way the misconception is typically treated by authority, that is, by "experts"--teachers, textbooks, popular media, and the like. The more that valued sources such as these promote the misconception, the more widely and strongly it will be held. In sum, according to the Conceptual Stability Scheme, the stability of a concept (and its related concepts) depends broadly on characteristics of the misconception itself, characteristics of the appropriate understanding to be achieved, differences between them, and various kinds of external sources of support.

One source of internal support has to do with the complexity of cognitive processing required for understanding a concept appropriately, in comparison to the processing involved in "understanding" the misconception. It is predicted that the less complex and taxing the processing for the misconception, in comparison to the more correct understanding, the more readily adopted and stable the misconception will be. For example, the concept as misunderstood might involve interpreting as linear, relationships that are actually nonlinear. Relevant dimensions of difficulty and complexity are listed below, with the less complex processing requirements listed first in each pair (taken from Feltovich et al., 1993, pp. 193-94):

--Concreteness/Abstractness. Are processes concrete and visualizable vs. abstract?

--Discreteness/Continuity. Are attributes and processes discrete or continuous?

--Sequentiality/Simultaneity. Do processes occur in a sequential, step-wise fashion, or are there aspects of simultaneity?

--Mechanism/Organicism. Are effects tractably traceable to the sequential actions of agents (mechanistic), or are they the product of more holistic, organic functions (see Pepper, 1942)?

--Separability/Interactiveness. Do different processes run independently of each other (or with only weak interaction), or are processes strongly interactive and multidimensional?

--Universality/Conditionality. Are there principles of function or relationships among entities that are universal in their application or validity, or are regularities much more local and context-dependent?

--Linearity/Non linearity. Are functional relationships among processes of entities linear or non-linear?

There are three other notable sources of internal support. These involve the structure of an individual's existing or prior knowledge as it relates to the correct and incorrect ideas. One we call "p-prim congruence," because it pertains to the

construct of a p-prim proposed by diSessa (1983). According to diSessa, a p-prim is a fundamental belief about how the world works; this is similar to what we, ourselves, have called a "prefigurative" scheme or "world view" (Feltovich et al., 1989). The more that components of a misconception are congruent with p-prims, and components associated with the correct interpretation are not, the more widespread and strongly held the misconception will be. The misconception will seem intuitive, and the correct conception will not. Another source of internal support involves available examples or analogies that seem to be in agreement with the misconception. Availability and salience in memory of phenomena that seem to conform to the misconception (or to its components) increase pervasiveness and stability of the misconception. A third knowledge-related source of support has already been mentioned and involves internal consistency or congruence among the components of the misconception. The extent to which components of a misconception bolster each other, reciprocate and make each other easier to believe, is particularly important in this regard.

Besides internal sources of support, there are other sources that are 'external' to the individual. These involve credence offered by authorities. Misconceptions may be taught or suggested in textbooks or taught by professors in classes. For example, one of the factors that contributes to the wide-spread and strongly held belief in a misconception about heart failure that has been the focus of other papers (Coulson et al., 1989; Feltovich et al., 1989) is that it is commonly proffered by medical textbooks and in clinical teaching.

Example Application of the Scheme to a Set of Concepts

In this section the Conceptual Stability Scheme is applied to a cluster of concepts in order to give a better sense of the scheme and its use. The set of ideas to be discussed are related to the concept of opposition to blood flow in the cardiovascular system, or what is termed "cardiovascular impedance." A short discussion of impedance is necessary as background.

The Concept of Cardiovascular Impedance

Cardiovascular impedance refers to the net effect of all factors that oppose the flow of blood in the cardiovascular system. There are three major sources of this opposition. One is resistance, which depends upon the length and diameter of blood vessels but also importantly upon the viscosity of the blood. Resistance exists in all fluid flow systems (even, for instance, in standard household plumbing) because for resistance to exist it does not matter whether the driving force (pressure) for the fluid is constant or changing. However, because the pressure produced by the beating heart is pulsatile, constantly changing, two sources of opposition besides resistance are germane. These other two embody the concepts of compliance and inertance.

The contributions that inertance and compliance make to opposition, like resistance, are dependent upon the length and diameter of the blood vessels.

However, unlike resistance, neither compliance nor inertance depends upon the viscosity of the blood. In addition, compliance is highly dependent upon the physical stiffness of the blood vessels. Inertance depends greatly upon the density of the blood moving in the vessels and represents the constant acceleration and deceleration of the mass of blood being moved in the vessels by the pulsatile pressure. Unlike resistance, the contributions that compliance and inertance ultimately make to the opposition to blood flow are totally dependent on the frequency with which the heart beats (the number of cycles of pressure and flow change the system undergoes per unit time).

In a complex manner, when compliance and inertance are considered in the context of the rate with which the heart beats, their contributions to the opposition to the flow of blood can be determined in the form of two additional constructs--compliant reactance and inertial reactance. These factors contribute to opposition to blood flow as really as resistance does, but, for the most part, as functions of different sources. Three main factors, then, contribute to the opposition to blood flow in the cardiovascular system: resistance, compliant reactance, and inertial reactance. However, the three do not combine in a straightforward manner to determine the total opposition to blood flow in the cardiovascular system. The total opposition is a vectorial, and not a scalar, additive function of the three basic components. *Hence, it is impossible to assess the total opposition without knowledge of all three factors, and their interaction is complicated.* In addition, it is not possible to judge the contribution of any one factor without consideration of the others. It is not possible to assess what effect a change in, say, vascular compliance will have on total opposition without knowing the status of the other factors. In particular, making the blood vessels more compliant (stretchy) can, under various different conditions, lead to a decrease, increase, or no change at all in total opposition to blood flow (depending the status of the other major contributors).

The main misconception used as an example in this section is this: that vascular compliance contributes to opposition to blood flow through the relative ability of more or less stretchy vessels to change their radii. (Compliance, again, is related to the ease with which a vessel can be stretched, by blood volume or pressure.) The misconception is that with greater compliance a vessel is more easily able to expand to incoming blood, thus assuming a greater radius and, in this way, offering less opposition to blood flow (through resistance factors affected by radius). Hence we will call this misconception the Compliance/Resistance misconception.

In this misconception, the role of compliance in opposition is treated in a resistance-like way, and this way of thinking further contributes to a widely held view of the entire cardiovascular system that is also highly resistance-based. That is, real factors of opposition that are not resistance-based are ignored or made to conform to a resistance kind of interpretation (as we will discuss regarding the role of compliance), a view of opposition that is more in conformance with systems involving constant driving pressure (e.g., a city water supply and household plumbing) than it is with the pulsatile cardiovascular system.

Our description of the Compliance/Resistance misconception and its role in learners' misconceptions about cardiovascular impedance is actually an

oversimplification of a complex misconception, involving several components (which will be elaborated below). However, the basic idea behind the misconception is that it is easier to push something into a vessel that has "flabby" walls than to push it into a vessel that has stiff walls. In reality, while a more compliant vessel will expand more to a given pressure, this expansion will be compensated by a greater recoil, as pressure falls (pressure in the cardiovascular system is cyclic), so that two vessels with otherwise similar characteristics, but different compliances, will have the same mean radii over the pulsation cycle. Hence, the contribution of compliance to opposition to blood flow cannot be through the misconstrued mechanism. In addition, even though greater compliance will make it easier to expand a vessel, it will also make it more difficult to change the pressure in the vessel (pressure is always changing in a cyclic pressure system), and, in a complex manner, it is this property that ultimately accounts for the role of compliance in opposition to blood flow. But, understanding the real role of compliance is difficult, requiring understanding of the cardiovascular system as a cyclic (alternating or AC "current"-- using an electrical analogy to fluid flow) pressure and flow system, and requiring understanding of interacting factors that are a function of continuous change of pressure and flow, rather than of the simple magnitude of either.

Although cardiovascular impedance and the contribution to it of vascular compliance are ultimately complicated, an admitted simplification may help convey a sense of the relevant concepts and the ways students misunderstand: All the energy (in the form of pressure) available to move blood is produced by the pumping action of the heart. Overcoming resistance, that is, overcoming internal bonding (viscous) forces within the blood so that the blood will move, depletes some of the total energy produced by the heart. Resistance would deplete some of the energy of the "pump" whether the pump were a constant pressure pump (like a vacuum cleaner, or roughly like the water tank on the edge of town) or an oscillating one like the heart. Because the heart *does* produce pulsatile pressure, two other sources of opposition come into play. Because of pulsatile pressure, some energy must be used to constantly accelerate and decelerate the blood--so, some energy is depleted in this inertance-related way in addition to that lost in overcoming resistance. In addition, because the heart produces pulsatile pressure and because the vessels are "stretchy" (compliant), some of the energy produced by the heart gets used in producing an actual, *real flow* into and out of the expanding and recoiling vessel walls, in addition to the flow that moves downstream through the circulation (see Figure 1-B). Like the blood flow that moves "downstream," this compliance-related flow has a resistance, compliance, and inertance. (One of the reasons some students have trouble understanding this flow as a legitimate flow is that they cannot believe it has a resistance. This is partly because they also wrongly believe that resistance is the result of some kind of frictional interaction between the blood and the blood vessel wall [see Figs. 3,6]--How could the compliance-related flow be a flow, and therefore have a resistance, if there is no wall to scrape against?) This compliance-related flow also costs energy. Most students have a reasonable understanding of resistance related to vessel width, vessel length, and blood viscosity, but even here they hold an "obstruction" (also, see DiSessa, 1983, "Ohm's p-prim") view, something blocking the passage of blood rather than depleting energy. Understanding cardiovascular impedance requires a change in point of

view with regard to "opposition," from one of opposition as something "blocking" or "fighting back" at some agent, to one something like "sapping the agent's strength."

Insert Fig. 1-B about here
(schematic-comp. flow)

The Scheme Applied to Cardiovascular Impedance and Related Conceptual Components

Application of the Conceptual Stability Scheme requires identification of the component and associated misconceptions that make up a particular misconception, so that the scheme can be applied to these and so that the interaction (e.g., reciprocation) among them can be studied. To convey some of the nature of this endeavor, the scheme is now applied to the misconception described above--compliance as having its effect through radius change--and to its allied misconceptions. This application of the scheme will be done using the following format:

COMPONENT MISCONCEPTION: A synopsis of a component misconception is given.

TEST ITEM: A "test item" statement involving the misconception is presented. These statements are from one of our studies (an Agree/Disagree study--more detail about this kind of study is given later) in which medical student subjects were presented a set of such statements and were required to express their extent of agreement with each statement (on a four point scale ranging from strongly disagree through disagree, agree, and strongly agree) and to explain the reasons for their choice. All quotes presented are from the same subject, *in order to convey the sense in which component misconceptions can cohere by supporting each other in an individual system of belief.* The test items are short-form devices for assessing the existence of a target misconception in students that were only possible to build after extensive laboratory work, involving more elaborate investigation, was conducted with regard to a set of misconceptions (see the section on "The Nature of the Relevant Studies," later).

RESPONSE: The subject's response to the test item is given, including the subjects' reasons for why she agreed or disagreed.

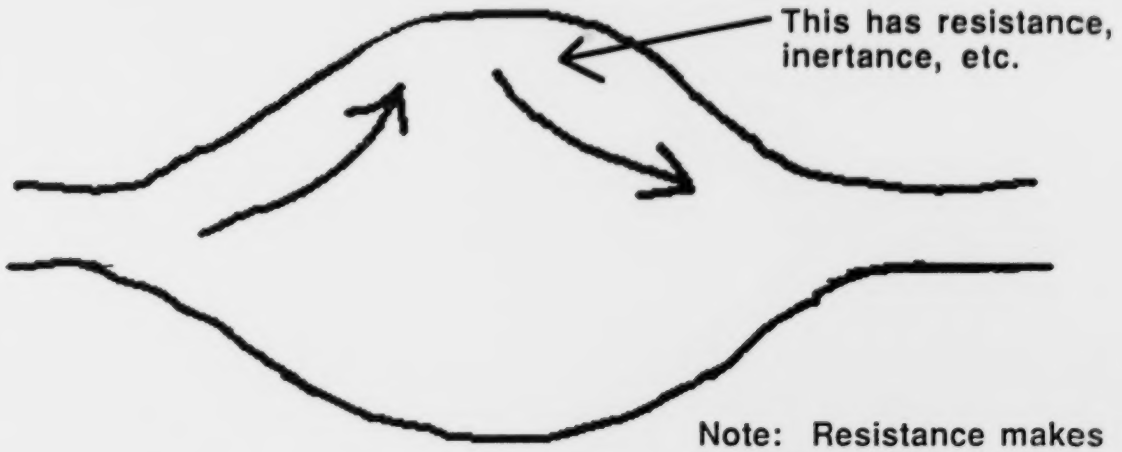
THE CORRECT IDEA: A description of correct understanding of the conceptual component is presented.

CONCEPTUAL STABILITY SCHEME: An analysis of the correct idea and the misconception, with regard to elements of the Conceptual Stability Scheme, is presented.

Components of the misconception involving the role of compliance in cardiovascular impedance are now presented according to the format just described, including selected instantiations of the Conceptual Stability Scheme for these components:

KEY ELEMENTS

(1) There is another (2nd) absolutely real flow



Note: Resistance makes no sense (here) if you believe resistance is from friction on side walls.

(2) Need new perspective on Opposition

deSessa: Ohm's p-prim

- Opposition is something that <u>fights back</u> at you

  force
  blockage etc.

- * Opposition is something that <u>depletes your strength</u>

  energy depletion

Fig 1-B

COMPONENT MISCONCEPTION (1) **(Compliance Acts through Radius).** According to this misconception. the contribution of compliance (or relative lack thereof) to opposition to blood flow is through the ability of a vessel to expand its radius. This misconception treats the role of compliance in opposition to blood flow as being a form of resistance (resistance being the oppositional factor that actually is largely dependent on radius): a more compliant vessel offers less opposition because it can "open up" to blood, forming a wider vessel with less resistance.

TEST ITEM: THE MORE COMPLIANT (STRETCHY) A VESSEL IS, THE LESS OPPOSITION TO BLOOD FLOW IT WILL PROVIDE BECAUSE THE MORE COMPLIANT VESSEL CAN MORE EASILY EXPAND ITS RADIUS TO LET BLOOD PASS THROUGH.

RESPONSE: "I strongly agree. The more stretchy a vessel is, or compliant, the fact that its radius, like it says here, its radius can get larger. And the fact that its radius can get larger decreases the resistance to the flow of blood through it, so that the blood can move faster with the less resistance that's provided."

THE CORRECT IDEA: The root of this problem lies in the idea that opposition to blood flow is only the product of how easy it is for a 'bolus' of blood to get to the next place in the circulation. What is not understood is that the circulation is a circuit with circuit elements. The compliance is a circuit element that is hooked in parallel with the resistance. Blood that flows into the compliance (the stretching of the vessel) does not directly continue on through the compliance and pass into or through the resistance. It must flow back out (AC or alternating flow) of the compliance while continuing on through the resistance. When oppositional elements are in parallel, the flow is mostly through the lesser oppositional elements. The AC components of flow, therefore, divide between the compliance and the resistance, with the majority going to the compliance (stretching the wall), which is a smaller oppositional factor than the resistance. It is easy for the flow (AC component) to get into the compliance compared with into the resistance, so most of it goes there (into the compliance). The non-alternating (the 'DC', or 'direct current' component of the flow--again, using an electrical analogy to fluid flow) component of flow does not go into the compliance at all, in any instantaneous sense. It just sets the mean about which the AC component of flow oscillates. In pulsatile (AC) flow, the size of a vessel oscillates equally above and below a mean size set by the direct (DC) component of flow. While a more compliant vessel will have wider 'swings' of size than a less compliant vessel, with greater decreases below the mean compensating for greater expansions above the mean, the mean size will be the same as for a less compliant vessel, as long as its other dimensions are the same; hence, the resistance aspects will be the same. The real role of compliance in opposition to blood flow is complicated and abstract, involving the property of compliance as an opposition to change-of-pressure (more compliance makes it harder to change pressure, which must be done continuously in a pulsatile pressure system) and the interaction of this property with numerous cardiovascular circuit properties (including the component frequencies of pressure/flow pulsation).

CONCEPTUAL STABILITY SCHEME: The misconception is concrete; one can easily envision blood pushing into and expanding a vessel, making its diameter wider. There is no way to envision the real role of compliance. It is difficult to reify opposition to change of pressure, let alone instantaneous opposition to change of pressure, and the ways that this could ever ultimately result in an opposition to the flow of blood. Causally, the misconception is mechanistic; the agent (blood) pushes open the object (the vessel) locally. In the correct notion, no such single agent can be identified as causing the contribution of compliance to opposition to blood flow, since this opposition is ultimately the emergent result of a number of simultaneous operative factors. Under the misconception, the contribution of compliance is linear, or at least monotonic--the more compliant the vessel, the greater the radius, the less the "resistance," the less the opposition. As has been noted earlier, the real contribution of degrees of compliance to degrees of opposition to blood flow is non-linear (that is, it contributes to a construct, compliant reactance, which itself combines in a vectorial way with other factors to determine the degree of impedance) and not easily describable at all.

COMPONENT MISCONCEPTION (2) **(Greater Compliance Implies Larger Mean Radius).** According to this misconception, for a given mean pressure (within a pulsatile pressure system), a more compliant vessel expands faster and closes down more slowly--hence, it runs at a higher mean radius. The idea that a vessel might close down during pulsation to something less than the mean radius is not in the picture--the vessel just oscillates above and down to something like the 'real' radius, which is a structural property of the vessel itself. This component misconception is particularly important: it is, perhaps, the key to reconciling the basically DC view that students have of many of the components of the cardiovascular system (interpretations that would be consistent with a heart that produced steady flow) with the fact that they know that the heart pulses and that vessels actually expand and rebound.

TEST ITEM (2) A: IN THE PULSING CARDIOVASCULAR SYSTEM, OF TWO VESSELS WHICH WOULD HAVE THE SAME DIAMETER AT CONSTANT PRESSURE (NOT PULSING), THE MORE COMPLIANT (STRETCHY) ONE WILL OPEN UP FASTER AND CLOSE DOWN MORE SLOWLY DURING PULSATION THAN THE STIFFER ONE, RESULTING IN A GREATER AVERAGE RADIUS FOR THE MORE COMPLIANT VESSEL.

RESPONSE (2) A: "I agree. I'm going to strongly agree because of the fact that the more compliant one will open up faster and will close down more slowly during pulsation than the stiffer one--because the stiffer one doesn't have the compliance and it can't open up as far and it's going to snap back real quick. So, therefore, there's a much greater average radius for the more compliant vessel and by having a greater radius, then it's going to have decreased resistance to blood flow. So the blood is going to go through faster than the stiffer one.".

ITEM (2) B: IN THE PULSING CARDIOVASCULAR SYSTEM, TWO VESSEL SEGMENTS WHICH WOULD HAVE THE SAME DIAMETER AT CONSTANT

PRESSURE (NOT PULSING) WILL BOTH HAVE THE SAME AVERAGE DIAMETER IN THE PULSING SYSTEM, EVEN THOUGH ONE IS HIGHLY COMPLIANT (STRETCHY) AND THE OTHER IS VERY STIFF.

RESPONSE (2) B: "I strongly disagree because if, if you have a constant pressure, if you have a constant pressure and both diameters are the same, so the radius of both vessels is the same, but if the cardiovascular system pulses so there is an increase in pressure at certain points in time, then the more compliant vessel is going to increase its radius with each pulse or with each minute increase in pressure, whereas the one that is very stiff isn't going to be able to increase its radius so its going to have a smaller radius and it's going to have more resistance to the flow. So, I would strongly disagree with the statement."

THE CORRECT IDEA: (Note, these two items and responses [(2) A & (2) B] are targeted at the same misconception, but the second expresses the item in a way which will elicit the opposite response from a subject who is consistently misunderstanding the concept: the subject can express the same misunderstanding in both a positive and negative fashion.) The operative mean size of a vessel, through cycles of pulsation, is a function both of structural properties of the vessel and of the magnitude of the DC component of flow (the AC component is always superimposed on the DC component). The DC component, or mean, sets the base degree of stretch in the vessel, which is always greater than the stretch that would exist if the circulation were empty. In general, the rate of stretch during the rising phase of the pulse is faster than the rebounding phase, but the distance traveled (by a point on the vessel wall) is the same out as in, and equal above and below the mean for every component frequency of the pulse. This is because each of the component frequencies of the pressure wave is a sinusoid, symmetrical about the mean. Because the component frequencies of the pulse are out of phase, the result of all of them together can look like an asymmetrical event, with a rising part which is faster (in velocity) than the falling part, but the distance traveled out and in must be the same--and the mean radii of two vessels differing in compliance but with otherwise identical properties would be the same.

CONCEPTUAL STABILITY SCHEME: A "real" radius for a vessel is easy to imagine, as when a tube is sitting on a table. A different, dynamic base width of a vessel, that only exists as an emergent property resulting from an embedded component (the "DC" part) of the total blood flow is more abstract. Oscillation above, and perhaps especially below, this dynamic base-level radius is also difficult to imagine. From early years of a student's schooling, oscillation is depicted as cycling around a zero value, assuming in the process both positive and negative values. Pendular movement in physics and alternating current electricity is likewise portrayed. Hence, there are likely numerous experienced examples that serve to define oscillation by swings around zero and by the presence of negative values. There are no negative values of pressure or flow in the cardiovascular system (which would amount to backwards flow) and no points where there is zero flow. This is because a constant level of flow (the 'DC' component) is superimposed upon the oscillatory component (the 'AC' component); oscillation is about some positive value rather than about zero. The wealth of examples of oscillation about a zero value leads students to believe that the cardiovascular system is not an alternating circuit

because, as students in our studies have claimed, "there is no backward flow." This may explain the failure, within the misconception just described, to account for the relatively (about the base state) negative radius changes that negate any expansion differences in vessels due to differences in their stretchability (i.e., their relative compliances).

COMPONENT MISCONCEPTION (3) **(Opposition is Monotonic with Stiffness).** By this misconception, only "stiffness" (lack of compliance) could ever provide opposition to blood flow. Greater compliance could never lead to greater opposition to blood flow. The contribution of stiffness to opposition to blood flow is a direct relationship--at least a monotonic (non decreasing) relationship.

TEST ITEM: INCREASING THE COMPLIANCE (STRETCHINESS) OF THE WALLS OF THE VESSELS OF THE CARDIOVASCULAR SYSTEM CAN INCREASE THE OPPOSITION TO BLOOD FLOW PROVIDED BY THE VASCULAR SYSTEM.

RESPONSE: "I strongly disagree because as you increase the compliance of the walls of the vessels, you're going to decrease the opposition to flow provided by the system. I mean, it's when you decrease the compliance that you increase the opposition to blood flow. So, if you're going to go ahead and make the walls more stretchy, the resistance to blood flow will decrease because the radius will become larger."

THE CORRECT IDEA: Greater 'stretchiness' or compliance in a vessel can even contribute to greater opposition to blood flow. The ultimate contribution of the degree of compliance to the total opposition to blood flow is a complex relationship, involving interactions among compliant reactance, inertial reactance, and resistance, as these interact with factors such as heart rate (more accurately, component frequencies of the pressure pulse). There can be situations in which an increase in compliance would lead to either an increase, decrease, or no change in opposition to blood flow.

CONCEPTUAL STABILITY SCHEME: A primary difference within the Conceptual Stability Scheme between the misconception and the correct notion is the p-prim congruence of the misconception relative to the correct idea. The idea that something that "complies," "gives way," or "accommodates" to blood (as a more compliant vessel is interpreted to do) could ever provide greater opposition to blood flow is highly counter-intuitive (in fact, it appears to clash with the "Ohm's p-prim" described by diSessa, 1983), in comparison to the direct relationship of greater opposition with greater stiffness embodied in the misconception. In addition, the correct relationship is non-linear (vectorial) and conditional (no universal statement of the impact of an increase/decrease in compliance on opposition to blood flow can be made) vs. linear and unconditional in the misconception.

COMPONENT MISCONCEPTION (4): **(Compliance Contribution is Independent of Heart Rate)** The contribution of lack of compliance (stiffness) to opposition to

blood flow will be independent of frequencies of pulsation--e.g., heart rate--since the contribution of compliance is a kind of resistance (which is independent of such frequencies)

TEST ITEM: THE OPPOSITION TO BLOOD FLOW PROVIDED BY THE VESSELS OF THE CARDIOVASCULAR SYSTEM DOES NOT DEPEND ON HEART RATE.

RESPONSE: "I strongly agree. Because it's not the--the resistance doesn't depend on the heart rate, it depends on the size of the vessels and the diameter of the walls. It doesn't have anything to do with heart rate, I hope."

THE CORRECT IDEA: The contribution from compliance (and from inertance, the other factor ultimately contributing to opposition to blood flow) is different from that of resistance. While the contribution from resistance is not dependent on the component frequencies of the pressure wave (as exemplified to a large extent by the heart rate), the contribution from compliance is dependent on such frequencies in a major way.

CONCEPTUAL STABILITY SCHEME: This misconception relies heavily on the notion that compliance acts like resistance, dependent mainly on vessel width or radius, a concrete and easily envisioned phenomenon. The actual factors that affect the contribution of compliance are highly abstract. The component frequencies of the pressure wave, upon which the contribution of compliance to opposition to blood flow is dependent, do not even have any clear physical embodiments (although heart rate is an approximation); they are mathematical abstractions that, nonetheless, have demonstrable implications for opposition to blood flow, through the effects of compliant and inertial reactance. Furthermore, the dependence of these reactances on components of the pressure wave is not linear. The component frequencies can affect compliant and inertial reactance, two sources of opposition to blood flow, differently -- so that the two sources might in different circumstances augment each other, diminish each other, or cancel out the effects of each other.

COMPONENT MISCONCEPTION (5) **(Opposition is Entirely Obstructional)**
According to this misconception, the contribution of lack of compliance (stiffness) to opposition to blood flow is a kind of resistance, with the same kind of properties as resistance. Compliance is not a fundamentally different kind of factor from resistance in its contribution to impedance. The only thing that opposes the flow of blood is physical obstruction (as exemplified by a wider or slimmer vessel).

TEST ITEM: THE ROLE THAT VESSEL STIFFNESS PLAYS IN OPPOSING THE FLOW OF BLOOD IS BASICALLY THE SAME AS THE ROLE THAT VESSEL RADIUS PLAYS IN OPPOSING THE FLOW OF BLOOD.

RESPONSE: "Well, I'm going to strongly agree because it's the stiffness that, if, if, the less stiff a vessel is, the more ability it has to increase its radius so they're somewhat related to each other because of the fact that the stiffness is, you know, if the vessel is more stiff, then its radius is going to be smaller than if it is less stiff,

when it can, you know, more compliance and it can open up more and decrease its opposition to flow."

THE CORRECT IDEA: See the correct idea section of COMPONENT MISCONCEPTION (1) above.

CONCEPTUAL STABILITY SCHEME: One problem in the student's interpretation involves not recognizing that the compliance and the resistance are different elements in the circuit sense. Because the same conduit, the blood vessel, is the physical location of both the compliance and the resistance (not to mention the inertance, the opposition to change of motion of blood) in the cardiovascular system, there is no salient cue to lead an individual to distinguish among the different functions served by the same vessel. This is in contrast to other analogous systems where such distinct functions are served by physically different components. In electrical systems, for example, 'resistors' and 'capacitors', the analogs of resistance and compliance respectively (not to mention 'chokes', the analog of inertance), are clearly discrete elements. Even if students' think about mechanical systems, the distinctness of 'dash pots' and 'springs' (not to mention 'masses') is clear also. Hence, numerous examples and analogies (e.g., from electricity) are available to reinforce the notion that importantly different functions must be performed by different physical structures in a system. In fluid systems, such as the cardiovascular system, the discreteness of different oppositional elements is just not overtly apparent. In our studies, the idea that a single physical structure (in this instance, the same blood vessel) can have different functional properties has persistently been difficult for our subjects to understand. This is exemplified, for example, in assertions that the small vessels are " resistance" vessels and the larger vessels are "storage" vessels (when, in fact, both kinds of vessels have both kinds of functions). In addition to having support from examples and analogies, the incorrect idea, that is, that different functions must be served by different physical structures, is more concrete. It also involves separability of structure/function, compared with the more correct view in which the same physical structure serves different functions, as a result of different interactions of the structure with some ongoing process (in this case, pulsatile flow).

This analysis of a misconception of the role compliance plays in the opposition to blood flow, in particular that it functions through the relative ability of vessels to expand their radii in response to the inflow of blood (or pressure) in a very resistance-like way, has illustrated that on many dimensions of comparison, components of the target misconception are simpler than the appropriate idea which fails to be understood. In addition, a set of misconceptions appear to be related to the target misconception, and to cohere in such a way that they provide mutual support. The misconception is also more concrete, carries with it more salient examples and analogies, and is more congruent with intuition (p-prim congruent). In such a situation we would expect the misconception to be widely held and to be difficult to change. This misconception of compliance (and the related resistance-based cardiovascular system) is, in fact, one of the more widely held misconceptions we have observed in our studies.

Educational Implications of the Conceptual Stability Scheme

The Conceptual Stability Scheme has general implications for education and educational research. Even when procedures are followed to isolate especially important concepts within a curriculum or within a text (e.g., by polling of teachers/practitioners, Dawson-Saunders et al., 1990; by analyzing results of old tests; or by some other means), it would be helpful to have some means to distinguish further among these the ones that are likely to require the most extensive and particularly tailored attention in instruction--because they are the more difficult to understand and/or the more difficult to emend when they are misunderstood. The Scheme is potentially useful for this purpose. In addition, in our own laboratories, the Scheme has been useful in directing us to good candidate concepts (and components) toward which to direct basic research about students' conceptual understanding and in suggesting aspects of these concepts that are likely to be troublesome for learners.

An important and perhaps novel characteristic of the Scheme is that is takes into consideration specified contrasts between the appropriate understanding of a concept to be learned and what are liable to be the misconceptions that develop. Hence, employing the Scheme requires at least expert advice/intuition on appropriate understanding and some input of information about likely misconceptions. Initially, these can come from the insights of teachers or from directed research. Iterations of instruction in the class and laboratory work, along related adjustments of the Scheme for a concept can help to refine initial analyses.

The Conceptual Stability Scheme will be useful for purposes such as these to the extent it is valid in predicting conceptual (and [mis]conceptual) stability in the sense we have defined--involving *pervasiveness, robustness, and constancy.* Research has been conducted on students' learning and understanding of cardiovascular impedance (and the related concept about the role of compliance), the topic analyzed in this report, that can provide an at least preliminary assessment of the worth of the Scheme in predicting results of learning and understanding for this set of concepts. The analyses of impedance and its related misconceptions presented in this report suggest that the misconceptions about impedance and compliance should be stable. This is because the appropriate understanding and the misconceptions differ with regard to the dimensions of the Scheme in many ways that would lead to the prediction that these misconceptions, once acquired, should be strongly held.

Pertinent research from our laboratory suggests that indeed both the general misconception, that opposition to blood flow is just a matter of resistance, and the more particular one, that casts compliance as operating in opposition through the ability of a vessel to expand and increase its radius, are stable in all three senses of stability we have proposed. The misconceptions are pervasive, in that many students hold them; robust, in that they are resistant to changing by instructional challenges; and they are consistent, with students exhibiting the same errors over periods of months. The entire detail of this experimentation is beyond the scope of the present report, but some pertinent aspects will be discussed briefly.

THE STABILITY OF A MiSCONCEPTION

A number of studies have been conducted that bear on the stability of the misconception discussed in the last section--that compliance works in opposition to blood flow through the ability of a vessel to increase (decrease) its radius (the Compliance/Resistance misconception). These studies will be described briefly at the beginning of this section, and then some results from the studies bearing on the stability (in the sense of Pervasiveness, Robustness, and Constancy) of the Compliance/Resistance misconception will be presented.

The Nature of the Relevant Studies

The authors' general approach in laboratory studies of learner's misconceptions has been to start investigations with wide-ranging, open-ended tasks and to cone down to more pin-pointed experimental tasks as we have gained better understanding of phenomena. The approach to the study of the Compliance/Resistance misconception has followed this form. The general kinds of studies that have been used in this effort are described next.

Probe-set studies. These involve wide-ranging, open-ended laboratory tasks that are used to provide clues to the nature of misconceptions students/learners may hold. They are used in the early stages of investigation of subjects' understanding of a concept and its close cluster of related concepts. Laboratory *materials* for these studies are what we have termed probe-sets. Each of these is a set of stimulus questions about a concept that includes both highly general and quite specific probes of a subject's understanding. A probe-set of questions has what we have called an "hour-glass" form. Initial parts of a set are very general and are meant to provide a wide-ranging appraisal of a subject's understanding of a concept before any prompting that might be associated with more directive questions about a concept. An example is "Discuss what factors contribute to opposition to the flow of blood in the cardiovascular system and how. " Probes narrow down progressively to highly specific ones, volunteering to the subject more information about the target concept as the questions get more specific. For example, a still relatively general probe such as "Define and discuss the following components of blood circulation and their role in opposition to blood flow: resistance, compliance, inertance," would be followed by very targeted queries (representing the skinny middle of the "hour glass"') about fundamental aspects of blood and blood circulation. "Define and discuss the following with respect to blood and blood vessels: radius, length, elasticity, viscosity,...etc." After these most basic of questions, the probe-set fans out again, this time from specific to general items, with questions that involve (in the case of the opposition to blood flow concepts) applications of the conceptual knowledge to problems (e.g., applications to cases of medical disease). (Probe -sets and their use are discussed in more detail in Feltovich et al., 1989)

Subjects for these studies have been of diverse kinds, from first and second year medical students to medical doctors and sub specialists. However, most of the subjects have been first and second year medical students, students in the process of studying the "basic science" of a medical school curriculum. In the laboratory *procedure* used, subjects are given Probe-set items, from the top of the "hour-glass" to the bottom, one item at a time. They are asked to respond as fully as they can to the items by talking aloud, telling an experimenter who is present when they have no more to say about a probe item. During the first pass through the probe-set, the subject and experimenter do not interact, except that the experimenter may ask the subject to speak up during periods of long silence. After a first pass through the entire probe-set, the experimenter may redirect the subject to some of the subject's own responses or to parts of the probe-set in order to gain better understanding of something the subject has done. Probe-set sessions typically last about two hours. Sessions are tape recorded and transcribed for analysis.

It was through probe-set studies that the nature of the Compliance/Resistance misconception (and its associated components) with regard to opposition to blood flow was gleaned initially (see more below under section on "Pervasiveness"). Having an approximate picture of a misconception allowed more focused investigation, as described next.

Agree/Disagree study. This study was conducted to clarify and embellish our initial interpretations of the target set of misconceptions associated with the Compliance/Resistance misconception. *Materials* for these studies were *agree/disagree propositions*, as described next. For each of the five hypothesized components of the misconception (see section on *"The Scheme Applied to Cardiovascular Impedance and Related Conceptual Components,"* earlier), the members of the research team, including one who is a cardiovascular physiologist, created a set of simple propositions Some of these were in conformance with the misconception component and some were in conflict with it, representing the more correct view. Twenty-four propositional items were created in this way and are shown in Figure 2.

Fig. 2 about here
(agree/disagree item examples)

A simple *agree/disagree rating scale* was used in this study This was a four point scale, with points on it labeled from left to right as strongly disagree, disagree, agree, strongly agree. There was also an accompanying space near the scale for the placement of a "confidence." The member of our research team who is a cardiovascular physiologist created a scoring key for all of propositions by rating all of them himself in terms of his degree of agreement/disagreement. (In general, in scoring subjects' responses, to be credited with being correct, a subject needed only to be on the correct side of the agree/disagree scale, e.g., if the scoring key correct response was "strongly agree." "agree" was counted as correct also).

Subjects for this study were the same as for the probe-set investigations, but with a special emphasis on second year medical students. The laboratory *procedure*

12. IN THE PULSING CARDIOVASCULAR SYSTEM, OF TWO VESSELS WHICH WOULD HAVE THE SAME DIAMETER AT CONSTANT PRESSURE (NOT PULSING), THE MORE COMPLIANT (STRETCHY) ONE WILL OPEN UP FASTER AND CLOSE DOWN MORE SLOWLY DURING PULSATION THAN THE STIFFER ONE RESULTING IN A GREATER AVERAGE RADIUS FOR THE MORE COMPLIANT VESSEL.

5. INCREASING THE COMPLIANCE (STRETCHINESS) OF THE WALLS OF THE VESSELS OF THE CARDIOVASCULAR SYSTEM CAN INCREASE THE OPPOSITION TO BLOOD FLOW PROVIDED BY THE VASCULAR SYSTEM.

11. IN THE PULSING CARDIOVASCULAR SYSTEM, TWO VESSEL SEGMENTS WHICH WOULD HAVE THE SAME DIAMETER AT CONSTANT PRESSURE (NOT PULSING) WILL BOTH HAVE THE SAME AVERAGE DIAMETER IN THE PULSING SYSTEM EVEN THOUGH ONE IS HIGHLY COMPLIANT (STRETCHY) AND THE OTHER IS VERY STIFF.

44. In the pulsing cardiovascular system, of two vessels which would have the same diameter at constant pressure (not pulsing), the more compliant (stretchy) one will have a greater average radius than the stiffer one.

9. THE MORE COMPLIANT (STRETCHY) A VESSEL IS, THE LESS OPPOSITION TO BLOOD FLOW IT WILL PROVIDE, BECAUSE THE MORE COMPLIANT VESSEL CAN MORE EASILY EXPAND ITS RADIUS TO LET BLOOD PASS THROUGH.

10. THE STIFFER A VESSEL IS, THE MORE OPPOSITION TO BLOOD FLOW IT WILL PROVIDE, BECAUSE IT IS HARDER FOR A STIFFER VESSEL TO EXPAND ITS RADIUS TO LET BLOOD PASS THROUGH.

31. THE RESISTANCE TO THE FLOW OF BLOOD IN A BLOOD VESSEL IS DUE TO THE FRICTION OF THE BLOOD SLIDING OVER THE VESSEL WALL SURFACE.

34. IT IS EASIER TO SHOOT A BULLET THROUGH A PIPE FILLED WITH AIR THAN A PIPE FILLED WITH WATER BECAUSE THE FRICTION OF THE BULLET SURFACE THROUGH THE WATER IS GREATER THAN THE FRICTION OF THE BULLET SURFACE THROUGH THE AIR.

37. BLOOD VISCOSITY (THICKNESS) AFFECTS RESISTANCE TO BLOOD FLOW BECAUSE MORE VISCOUS BLOOD EXERTS MORE FRICTION ON THE SURFACE OF THE VESSEL WALL THAN DOES LESS VISCOUS BLOOD.

30. THE RESISTANCE TO THE FLOW OF BLOOD IN A VESSEL ULTIMATELY RESULTS, IN A LARGE PART, FROM THE BLOOD IN CONTACT WITH THE VESSEL WALL BEING STATIONARY.

Fig. 2

3. INCREASING THE STIFFNESS IN THE WALLS OF THE VESSELS OF THE CARDIOVASCULAR SYSTEM, WILL ALWAYS INCREASE THE OPPOSITION TO BLOOD FLOW PROVIDED BY THE VASCULAR SYSTEM.

4. INCREASING THE COMPLIANCE (STRETCHINESS) OF THE WALLS OF THE VESSELS OF THE CARDIOVASCULAR SYSTEM WILL ALWAYS DECREASE THE OPPOSITION TO BLOOD FLOW PROVIDED BY THE VASCULAR SYSTEM.

18. THE CONTRIBUTION THAT VESSEL STIFFNESS ULTIMATELY MAKES TO THE OPPOSITION TO BLOOD FLOW IS INDEPENDENT OF THE RATE WITH WHICH THE HEART BEATS.

45. In the pulsing cardiovasvcular system the pulse is imposed on top of the diastolic pressure such that the pulse rises up from the diastolic pressure and falls back down to the diastolic pressure.

19. THE RATE WITH WHICH THE HEART BEATS DOES AFFECT THE CONTRIBUTION THAT VESSEL STIFFNESS MAKES TO OPPOSITION TO BLOOD

16. THE ROLE THAT VESSEL STIFFNESS PLAYS IN OPPOSING THE FLOW OF BLOOD IS BASICALLY THE SAME AS THE ROLE THAT VESSEL RADIUS PLAYS IN OPPOSING THE FLOW OF BLOOD.

21. THE OPPOSITION TO BLOOD FLOW PROVIDED BY THE VESSELS OF THE CARDIOVASCULAR SYSTEM IS HIGHLY DEPENDENT UPON HEART RATE.

48. The viscosity of the blood, and the diameter and length of the blood vessels are all that matter in opposing the flow of blood in the cardiovascular system.

17. THE ROLE THAT VESSEL STIFFNESS PLAYS IN OPPOSING THE FLOW OF BLOOD IS FUNDAMENTALLY DIFFERENT THAN THE ROLE THAT VESSEL RADIUS PLAYS IN OPPOSING THE FLOW OF BLOOD.

20. THE OPPOSITION TO BLOOD FLOW PROVIDED BY THE VESSELS OF THE CARDIOVASCULAR SYSTEM DOES NOT DEPEND ON HEART RATE.

47. Physical factors that retard the movement of blood downstream through the circulation and that inhibit its passage through the vessels are all that matter in opposing the flow of blood in the cardiovascular system.

49. The opposition to blood flow in the cardiovascular system is made up of a host of factors, in addition to blood viscosity and vessel diameter and length, which compete for the pressure (or energy) produced by the heart.

35. IT IS EASIER TO SHOOT A BULLET THROUGH A PIPE FILLED WITH AIR THAN THROUGH A PIPE FILLED WITH WATER IN LARGE PART BECAUSE IT IS HARDER TO DEFORM THE WATER THAT IS NOT IN CONTACT WITH THE BULLET THAN IT IS TO DEFORM THE AIR THAT IS NOT IN CONTACT WITH THE BULLET.

Fig 2 (con't)

6. MAKING THE VESSELS OF THE CARDIOVASCULAR SYSTEM MORE COMPLIANT (SO THEY STRETCH EASIER) MAY NOT CHANGE THE OPPOSITION TO BLOOD FLOW PROVIDED BY THE VESSELS AT ALL.

Fig 2 (con't)

was that subjects were given one propsitional statement, along with a rating scale, at a time; they were directed to read the statement, to mark the scale for their degree of agreement or disagreement with the statement, to write a confidence (0-100%) in their rating, and to explain aloud why they decided everything as they did. All of this was done under the direction to subjects to vocalize their thoughts. Again, one pass through the set of agree/disagree items was conducted without intervention by the experimenter (except to hand the subject the items and encourage the subject to talk), but clarifying interactions could occur after the first full pass.

The agree/disagree study enabled still better understanding of the misconceptions and their nuances, setting the stage for the instructional study, to be described next. It was from the agree/disagree study that the quotes from a subject shown in the section of this report titled *The Scheme Applied to Cardiovascular Impedance and Related Conceptual Components* were taken. Results from the agree/disagree study also suggested the need for a sixth component for the Compliance/Resistance misconception. This involves the causal basis for resistance in a fluid flow system (and will be described more fully later in this report).

Instructional/ challenge study. In the "instructional study," an attempt was made to change misconceptions associated with the Compliance/Resistance misconception by providing to subjects directive challenges to these erroneous beliefs. In addition to the five components of the misconception that have been discussed, a sixth, involving the cause of resistance in fluid flow systems, was added (see Figure 3), since its presence was suggested so strongly in the results of the agree/disagree study. *Materials* created for each component misconception included a progressively more challenging set of propositions that were at once true and, hence, discrepant with the component misconception, but could also serve to guide the subject to a more appropriate understanding. For example, the ordered sets built for component Misconceptions #1 and #5 (see Fig. 3 and section *"The Scheme Applied to Cardiovascular Impedance and Related Conceptual Components "*) are given in Figures 4-A and 4-B (ignoring for the moment statements labeled #16, #17, #48 and #49 at the tops of those figures). (Note, the last item, 71b, in Figure 4-B is much longer than other items from our studies. This item was seen last within the instructional blocks by subjects and was designed to be an integrative and summary item) These sequences were designed simultaneously to break down the misconception and to build up in subjects a more correct view. Both a pre and a post-test were also created for the instructional studies. This was done by taking the propositional items from the agree/disagree studies and randomly assigning about half to the pretest and about half to the post-test.

Fig. 3 about here
(Six components of Comp/Res)

Fig. 4a,b about here
(Instruction set for Miscon #1,5)

The twenty *Subjects* for the instructional study were like those of the agree/disagree study, primarily second year medical students, but with a smattering

MISCONCEPTIONS

Misconception #1
Compliance functions in opposition through ability to change radius, allowing greater flow downstream.

Misconception #2
Greater compliance in a vessel implies that it operates at a higher mean radius.

Misconception #3
Opposition to blood flow is monotonic with stiffness - the greater the stiffness, the greater the contribution to opposition to flow.

Misconception #4
The role that compliance plays in opposition to blood flow is independent of the heart rate.

Misconception #5
Opposition to blood flow is entirely obstructional (vs. notion of competition for energy or whatever).

Misconception #6
Resistance is caused by friction or some other direct interaction between the blood and the vessel wall.

Fig. 3

16. The role that vessel stiffness plays in opposing the flow of blood is basically the same as the role that vessel radius plays in opposing the flow of blood.

17. The role that vessel stiffness plays in opposing the flow of blood is fundamentally different than the role that vessel radius plays in opposing the flow of blood.

50b. As a vessel expands during the ascending phase of a pulse, this does not mean that all of the blood in the expanded vessel simply flows downstream through a now larger vessel, since some of it, for instance, flows into the expansion of the vessel itself.

51b. In the pulsing cardiovascular system the ability of the more compliant (stretchy) vessel to expand its radius during the pulse does not affect the resistance of the vessel (which affects the flow downstream) because the resistance depends upon the average radius of the vessel which can be the same whether the vessel is stiff or stretchy.

52b. In the cardiovascular system, vessel radius contributes to how difficult it is for blood to flow downstream though the circulation. Vessel stiffness helps determine the compliance of a blood vessel, which contributes to how difficult it is for blood to flow into and out of the bulging of the vessel wall during a pulse.

53b. In the pulsing cardiovascular system blood flows:
1) into and back out of the expanding and contracting vessel; and
2) downstream through the vessel.
The more compliant (stretchy) the vessel is the easier it is for the blood to flow into stretching it rather than flowing downstream. The stiffer the vessel is the more difficult it is for blood to flow into stretching it, allowing more of it to flow downstream.

54/69b. In the pulsing cardiovascular system some of the energy produced by the heart is used up in making blood flow into and out of the the expansion of vessel walls. Hence, factors associated with flow into and out of the vessel walls such as wall stiffness and heart rate contribute to opposition to blood flow.

REPEAT PAIR of #16 and #17.

Fig 4-A

Misconception #5

48. The viscosity of the blood, and the diameter and length of the blood vessels are all that matter in opposing the flow of blood in the cardiovascular system.

49. The opposition to blood flow in the cardiovascular system is made up of a host of factors, in addition to blood viscosity and vessel diameter and length, which compete for the pressure (or energy) produced by the heart.

67b. In the cardiovascular system not all of the energy generated by the heart is used up in making blood flow downstream through the resistance of the circulation. Other factors involving heart rate, stretchiness of the vessels, and the density of the blood compete for the energy generated by the heart and thus contribute to opposition to blood flow.

68b. Pressure generated by the heart provides the energy to circulate the blood in the cardiovascular system. Any factor that detracts from this pressure energy and hence makes less of it available to propel blood through the circulation is a source of opposition to blood flow.

69/54b. In the pulsing cardiovascular system some of the energy produced by the heart is used up in making blood flow into and out of the the expansion of vessel walls. Hence, factors associated with flow into and out of the vessel walls such as wall stiffness and heart rate contribute to opposition to blood flow.

70b. In the cardiovascular system some of the energy produced by the heart is used up in accelerating and decelerating blood with every beat of the heart. Hence, factors associated with accelerating and decelerating blood such as blood density and heart rate contribute opposition to blood flow.

71b. The energy provided by the pumping action of the heart that drives blood in the circulation has the form of pressure. This pressure is not constant in the cardiovascular system but changes rhythmically with the pulse. As blood moves through oppositional elements in the circulation, the pressure drops as energy is converted into movement of blood. Some of the pressure energy is converted into downstream movement of the blood by dropping across the resistance of the blood vessels. All pressure drops across resistance whether it is pulsing or not. Another portion of the pressure energy is converted into back and forth movement of blood as the vessels bulge out and recoil back in during the pulse. This pressure is said to drop across the compliant reactance. Still another portion of the pressure energy is converted into acceleration and deceleration of the blood in response to the pulse and is said to drop across the inertial reactance. Only pulsing pressure drops across the elements of compliance and inertance. Energy is consumed (i.e., the pressure drops) by blood moving across all three of these elements (resistance, compliant reactance, and inertial reactance) and thus all are factors which contribute to the opposition to the flow of blood. Since the pressure energy in the pulse is fixed at the time it leaves the heart any element that drops pressure, besides the resistance, will reduce the energy available to drive blood through the resistance and in this way opposes the flow of blood downstream. Since resistance, compliant reactance, and inertial reactance combine in a complex (vectorial) way, it is not a simple matter to specify exactly how a change in any one of these will affect the total opposition to blood flow (the cardivascular impedance). However, it is clear that there is more to opposition to the flow of blood in the cardiovascular system than just vascular resistance.

REPEAT PAIR of #48 and #49.

Fig 4-B

of others. The *procedure/design* for the instructional study is outlined in Figure 5. Each subject was first presented items from the pretest, under the same procedure and directions as these were encountered and responded to in the agree/disagree studies. The subject then was presented with six instructional blocks, one for each component misconception. Within the block for each component misconception, a subject was first presented with two familiar "discriminator" propositions (e.g., items #16, #17 of Fig. 4) for that misconception, then the ordered instructional set of propositions for that component misconception, and then the same two discriminator items again (after "instruction"). After completing the six instructional blocks, the subject then was presented with the post-test. These post-test items for the instructional study were the propositions from the agree/disagree studies not used in the pre-test for the instructional study. All items in the instructional study, whether pre-test, discriminator, instructional, or post-test, were addressed in the same way by the subjects. Subjects read each item, rated their agreement/disagreement with it on a four point scale, declared a confidence in this judgment, and explained their reasons for making the judgment they did.

Fig. 5 about here
(Design-instruction studies)

Results from these studies pertinent to the stability of the Compliance/Resistance misconception are presented next, organized by the major factors of conceptual stability: Pervasiveness, Robustness, and Constancy.

Pervasiveness of the Misconception

Pervasiveness has to do with how widely within a pertinent population a conceptual belief is held. Findings from all of our studies have shown that the Compliance/Resistance misconception (in brief, that compliance--"stretchiness" --of a vessel affects opposition to blood flow through the ability of a more compliant vessel to open up to an increased pressure or flow of blood, expanding its radius) is very widely held among medical students (as well as by many medical professionals).

For example, in a Probe-set study involving fourteen first and second year medical students (7 first year, 7 second year), a version of the role of vascular compliance in opposition to blood flow very similar to the Compliance/Resistance misconception was volunteered by eleven of the fourteen students (79%). Figure 6 shows some of these descriptions given by the students from that study. This study also provided some clues to misconceptions that are associated with the primary misconception. For example, Fig. 6 also shows some of the subject protocol descriptions that suggested that students holding the Compliance/Resistance misconception might also believe that resistance to blood flow is the result of some kind of frictional interaction between the blood and the surface of the vessel wall (component Misconception #6--Fig. 3.)

STRUCTURE OF CHALLENGE/INSTRUCTION STUDY

* PREVIEW PRETEST	1/2 OF ITEMS FROM SIMPLE AGREE DISAGREE STUDY ALL BEAR ON MISCONCEPTIONS 1-6
* INSTRUCTION	6 BLOCKS (SIX COMPONENTS) EACH BLOCK (EACH MISCONCEPTION) Two flip flop items from pretest * Instructional vignettes Two flip flop items again
*POSTEST	THE OTHER 1/2 OF ITEMS FROM AGREE/DISAGREE STUDY

20 STUDENTS
2-3 HOURS

* "INSTRUCTION" ARE TRUE DESCRIPTIONS THAT TRY BOTH TO UNDERMINE OLD AND BUILD BETTER COMPONENTS. HIGHLY GUIDED BY THE NATURE OF THE COMPONENT.

NOT INTERACTIVE

Fig 5.

Fig. 6 about here
(Probe study--component miscons)

In addition, it was an entirely different type of study, the agree/disagree study, that provided the exemplar protocols indicating belief in the components of the Compliance/Resistance misconception that were presented in the section on *"The Scheme Applied to Cardiovascular Impedance and Related Conceptual Components"* . Figure 7-A lists the propositional items from that agree/disagree study that were answered incorrectly most often in the study. These can be seen to be fairly clear statements of the various components of the Compliance/Resistance misconception or of their correct alternatives. Figure 7-B shows subjects' performance on all items of the agree/disagree study, along with the component misconception to which each item pertains (this figure can be aligned with Fig. 2, if the reader wishes to view the actual test items corresponding to the item numbers given in Fig 7-B). Except for items corresponding to components 4 and 5 of the Compliance/Resistance misconception, performance was poor. Items for 4 and 5 were often answered correctly but for the wrong reasons (see later), in ways that actually gave support to the existence of these component misconceptions.

Fig. 7-A about here
(Agree/Dis study--most missed)

Fig. 7-B about here
(Agree/Dis study--subject performance)

Figure 8 gives the propositional elements most often answered incorrectly in an instructional study. These can be seen to be quite similar to the items listed in Fig. 7-A and, again, they implicate the components of the Compliance/Resistance misconception. Figure 9 shows an actual student response from the agree/disagree study to the first proposition listed in Fig 7-A (as one of the items most often answered incorrectly). It shows how strongly students can hold and defend components (in this case, Component #2--see Fig. 3 and the section on *the Scheme Applied to Cardiovascular Impedance and Related Conceptual Components"*) of the Compliance/Resistance misunderstanding.

Fig. 8 about here
(Inst. study--most missed)

Fig. 9 about here
(Agree/Dis--protocol)

The performance of subjects on component misconception #4, regarding the independence of opposition to blood flow and heart rate (see Fig. 3 and the section on *The Scheme Applied to Cardiovascular Impedance and Related Conceptual Components)* was complicated and requires special explanation. Since it was predicted that subjects would hold a resistance- based model of opposition, it was also predicted

SOME FINDINGS FROM EARLY "PROBE" STUDIES
(Compliance and Resistance)

Compliance in Relation to Opposition (Expanding Radius)
(11/14 Students--79%)

(MS1-S2)

Elasticity: The more elastic a vessel is, the greater compliance it will have so that ah, a vessel that can stretch easily will be more likely to accommodate flow because it won't present as great a resistance to that flow if it can expand in the, in the face of increasing pressure or whatever. So, in general, I would say that the more elastic a vessel the more compliant it would be and the lower the, the pressure will be, the greater, the less the resistance, the easier the flow.

Um, the less compliant a vessel the more resistance it's going to have to blood flow. That just seems to make sense that if a blood vessel is less compliant it's going to have ah, less ability to increase its size. It's going to be smaller in diameter or radius, um, so therefore, it's resistance one creates because um, the smaller the diameter, or radius, or whatever the resistance is going to be larger. On the other hand, on the other hand, if you have an increased compliance it's going to decrease the resistance of the vessel and blood flow should increase.

(MS1-S6)

Elasticity: ... In regard to opposition to blood flow, elasticity is responsible for decreasing opposition to blood flow because the elastile elements in blood vessels that are able to ah, stretch to a, ah, rather remarkable degree and, um, will allow the amount of blood flowing through them in most cases to ah, pass through with the least amount of resistance. Um, all blood vessels have their limit and ah, and ah, when that is met opposition would then increase.

Wall Friction in Relation to Resistance
(4/14 Students--29%)

(MS2-S1)

Viscosity: the blood is more viscous and more thick, then it's going to be flowing less fast, it is going to be flowing than it would if it were nice and fluidy and more like water. That is because the more viscous it is the more friction it is going to have against the vessels it is running through.

(MS1-S1)

The first thing I think about is friction on the inside of vessels... friction is just something that will, can't be changed. I would say that that's a constant, friction within the blood vessel itself. And that will, that will occur throughout the entire system.(factors contributing to opposition)

Fig 6

AGREE/DISAGREE
Most Difficult Items
(descending order)

12. IN THE PULSING CARDIOVASCULAR SYSTEM, OF TWO VESSELS WHICH WOULD HAVE THE SAME DIAMETER AT CONSTANT PRESSURE (NOT PULSING), THE MORE COMPLIANT (STRETCHY) ONE WILL OPEN UP FASTER AND CLOSE DOWN MORE SLOWLY DURING PULSATION THAN THE STIFFER ONE RESULTING IN A GREATER AVERAGE RADIUS FOR THE MORE COMPLIANT VESSEL.

No. correct = 0, % correct = 0

5. INCREASING THE COMPLIANCE (STRETCHINESS) OF THE WALLS OF THE VESSELS OF THE CARDIOVASCULAR SYSTEM CAN INCREASE THE OPPOSITION TO BLOOD FLOW PROVIDED BY THE VASCULAR SYSTEM.

No. correct = 0, % correct = 0

11. IN THE PULSING CARDIOVASCULAR SYSTEM, TWO VESSEL SEGMENTS WHICH WOULD HAVE THE SAME DIAMETER AT CONSTANT PRESSURE (NOT PULSING) WILL BOTH HAVE THE SAME AVERAGE DIAMETER IN THE PULSING SYSTEM EVEN THOUGH ONE IS HIGHLY COMPLIANT (STRETCHY) AND THE OTHER IS VERY STIFF.

No. correct = 0, % correct = 0

44. IN THE PULSING CARDIOVASCULAR SYSTEM, OF TWO VESSELS WHICH WOULD HAVE THE SAME DIAMETER AT CONSTANT PRESSURE (NOT PULSING), THE MORE COMPLIANT (STRETCHY) ONE WILL HAVE A GREATER AVERAGE RADIUS THAN THE STIFFER ONE.

No. correct = 0, % correct = 0

9. THE MORE COMPLIANT (STRETCHY) A VESSEL IS, THE LESS OPPOSITION TO BLOOD FLOW IT WILL PROVIDE, BECAUSE THE MORE COMPLIANT VESSEL CAN MORE EASILY EXPAND ITS RADIUS TO LET BLOOD PASS THROUGH.

No. correct = 1, % correct = 11.1

10. THE STIFFER A VESSEL IS, THE MORE OPPOSITION TO BLOOD FLOW IT WILL PROVIDE, BECAUSE IT IS HARDER FOR A STIFFER VESSEL TO EXPAND ITS RADIUS TO LET BLOOD PASS THROUGH.

No. correct = 0, % correct = 0

31. THE RESISTANCE TO THE FLOW OF BLOOD IN A BLOOD VESSEL IS DUE TO THE FRICTION OF THE BLOOD SLIDING OVER THE VESSEL WALL SURFACE.

No. correct = 1, % correct = 11.1

#4 Answered Right for wrong reasons

Fig 7-A

	ITEM #	Miscon. #	MEAN	Std. Dev.	Std. Err.	Variance	% Correct
1	12ER	2	2.556	.726	.242	.528	0
2	5ER	3	2.556	.527	.176	.278	0
3	11ER	2	2.444	.726	.242	.528	0
4	44ER	2	2.400	.548	.245	.300	0
5	9ER	1	2.222	.972	.324	.944	11.1
6	10ER	1	2.222	.972	.324	.944	0
7	31ER	6	2.222	.667	.222	.444	11.1
8	34ER	6	2.111	.928	.309	.861	11.1
9	37ER	6	2.111	.782	.261	.611	11.1
10	30ER	6	1.889	.601	.200	.361	11.1
11	3ER	3	1.778	.833	.278	.694	22.2
12	4ER	3	1.778	.833	.278	.694	22.2
13	18ER	4	1.667	1.000	.333	1.000	44.4
14	45ER	2	1.600	.894	.400	.800	20.0
15	19ER	4	1.444	1.236	.412	1.528	66.6
16	16ER	1	1.333	.500	.167	.250	0
17	21ER	4	1.222	1.093	.364	1.194	77.7
18	48ER	5	1.200	.447	.200	.200	80.0
19	17ER	1	1.111	.601	.200	.361	11.1
20	20ER	4	1.111	1.167	.389	1.361	77.7
21	47ER	5	1.000	.707	.316	.500	80.0
22	49ER	5	1.000	.707	.316	.500	80.0
23	35ER	6	.778	.667	.222	.444	77.7
24	6ER	3	.667	.707	.236	.500	44.4

AGREE/DISAGREE STUDY

Fig. 7-B.

10 CHALLENGE
Most Difficult Items
(descending order)

44. IN THE PULSING CARDIOVASCULAR SYSTEM, OF TWO VESSELS WHICH WOULD HAVE THE SAME DIAMETER AT CONSTANT PRESSURE (NOT PULSING), THE MORE COMPLIANT (STRETCHY) ONE WILL HAVE A GREATER AVERAGE RADIUS THAN THE STIFFER ONE.

5. INCREASING THE COMPLIANCE (STRETCHINESS) OF THE WALLS OF THE VESSELS OF THE CARDIOVASCULAR SYSTEM CAN INCREASE THE OPPOSITION TO BLOOD FLOW PROVIDED BY THE VASCULAR SYSTEM.

34. IT IS EASIER TO SHOOT A BULLET THROUGH A PIPE FILLED WITH AIR THAN A PIPE FILLED WITH WATER BECAUSE THE FRICTION OF THE BULLET SURFACE THROUGH THE WATER IS GREATER THAN THE FRICTION OF THE BULLET SURFACE THROUGH THE AIR.

11. IN THE PULSING CARDIOVASCULAR SYSTEM, TWO VESSEL SEGMENTS WHICH WOULD HAVE THE SAME DIAMETER AT CONSTANT PRESSURE (NOT PULSING) WILL BOTH HAVE THE SAME AVERAGE DIAMETER IN THE PULSING SYSTEM EVEN THOUGH ONE IS HIGHLY COMPLIANT (STRETCHY) AND THE OTHER IS VERY STIFF.

44a. IN THE PULSING CARDIOVASCULAR SYSTEM, OF TWO VESSELS WHICH WOULD HAVE THE SAME DIAMETER AT CONSTANT PRESSURE (NOT PULSING), THE MORE COMPLIANT (STRETCHY) ONE WILL HAVE A GREATER AVERAGE RADIUS THAN THE STIFFER ONE.

10. THE STIFFER A VESSEL IS, THE MORE OPPOSITION TO BLOOD FLOW IT WILL PROVIDE, BECAUSE IT IS HARDER FOR A STIFFER VESSEL TO EXPAND ITS RADIUS TO LET BLOOD PASS THROUGH.

51B. IN THE PULSING CARDIOVASCULAR SYSTEM THE ABILITY OF THE MORE COMPLIANT (STRETCHY) VESSEL TO EXPAND ITS RADIUS DURING THE PULSE DOES NOT AFFECT THE RESISTANCE OF THE VESSEL (WHICH AFFECTS THE FLOW DOWNSTREAM) BECAUSE THE RESISTANCE DEPENDS UPON THE AVERAGE RADIUS OF THE VESSEL WHICH CAN BE THE SAME WHETHER THE VESSEL IS STIFF OR STRETCHY.

11a. IN THE PULSING CARDIOVASCULAR SYSTEM, TWO VESSEL SEGMENTS WHICH WOULD HAVE THE SAME DIAMETER AT CONSTANT PRESSURE (NOT PULSING) WILL BOTH HAVE THE SAME AVERAGE DIAMETER IN THE PULSING SYSTEM EVEN THOUGH ONE IS HIGHLY COMPLIANT (STRETCHY) AND THE OTHER IS VERY STIFF.

Fig. 8

4. INCREASING THE COMPLIANCE (STRETCHINESS) OF THE WALLS OF THE VESSELS OF THE CARDIOVASCULAR SYSTEM WILL ALWAYS DECREASE THE OPPOSITION TO BLOOD FLOW PROVIDED BY THE VASCULAR SYSTEM.

12. IN THE PULSING CARDIOVASCULAR SYSTEM, OF TWO VESSELS WHICH WOULD HAVE THE SAME DIAMETER AT CONSTANT PRESSURE (NOT PULSING), THE MORE COMPLIANT (STRETCHY) ONE WILL OPEN UP FASTER AND CLOSE DOWN MORE SLOWLY DURING PULSATION THAN THE STIFFER ONE RESULTING IN A GREATER AVERAGE RADIUS FOR THE MORE COMPLIANT VESSEL.

Fig 8 (con'E)

#45d. In the pulsing cardiovascular system of two vessels which would have the same diameter at constant pressure, the more compliant (stretchy) one would open up faster and close down more slowly during pulsation than the stiff one resulting in a greater average radius for the more compliant vessel.

"This is exactly true. I strongly agree, that's what I was trying to say before when they asked me whether ah, whether ah, it would have an average ah, whether the average radius would be the same or not. What I meant to say was that it would open up faster and close down more slowly because it's more, more compliant um, (pause) okay? Um, um, if they had a constant pressure, a constant diameter would not pulsing when it does pulse the blood does rush in there and the that's ah, more compliant is gonna expand faster and it will close down more slowly later because ah, there'll be less push against the blood to, to, to push it out, so it'll have a greater average radius. My confidence rating on that is very high, 80%."

Fig. 9

that subjects would believe opposition to be *independent of heart rate*, since resistance is unaffected by the rate with which the heart beats and rate affects only inertance and compliance-based contributors to opposition.

Subjects instead nearly uniformly claimed opposition to be *dependent* on heart rate, but for reasons that reflected belief in the Compliance/Resistance misconception more clearly than could have been predicted in advance. These responses took a number of forms, three particularly noteworthy. One is intimately related to the misunderstandings exhibited by the subject in Fig. 9. If one believes, as the subject portrayed there does, that with greater and greater compliance a vessel expands progressively more on each beat than it contracts, then if there are more frequent beats, under this erroneous model the more compliant vessel would spend a greater portion of its time at a bigger radius. This (mis)understanding is an entirely logical concomitant of the other components of the Compliance/Resistance misconception but was not envisioned in advance by the investigators; the subjects answered "correctly," but for reasons consistent with the misconception they were expected to hold. The bases for two other kinds of correct-looking responses to items representing component #4 were similar. In one, students, believing that an increase in *rate* of blood flow through a vessel implies an increase of blood *volume* there (see Fig. 1; also Feltovich et al., 1989; 1993) and hence a greater radius, therefore also believe that a greater heart rate produces bigger-radius, less oppositional vessels. Other subjects believed that every recoil of a vessel during a heart beat produces some back-flow of blood toward the heart, opposing downstream flow (see Fig 19, later). Hence, under this faulty thinking, a greater heart (beating) rate would produce more of this kind of opposition.

The pervasiveness of the Compliance/Resistance misconception and its related elements will be further accentuated as results from the various kinds of studies continue to be discussed. The bulk of the evidence indicates that the Compliance/Resistance misconception is pervasively held by learners of cardiovascular physiology and cardiovascular medicine.

Robustness of the Misconception

We define *robustness* of a conceptual belief to be its resistance to change from challenges to its credibility. The most direct evidence for the robustness of the Compliance/Resistance misconception comes from the instructional study, where faulty beliefs associated with the Compliance/Resistance misconception were confronted by carefully designed alternative instructional vignettes that directly countered the beliefs students were expected to hold. Recall that the instructional study utilized a pre and a post-test created from random assignment of true and false statements from the agree/disagree study, all bearing on the role of compliance in opposition to blood flow. If subjects were to change their beliefs in a more appropriate direction as a result of the intervening "instruction" in the instructional study, one would expect improvement in the post-test performance. In fact, subjects did not improve their performance from pre to post-test.

Figure 10 shows the percentage of correct responses to propositions in both the pre- and post-tests for twenty second year medical students from the instructional study (again, to be credited with being correct, a subject needed only to be on the correct side of the agree/disagree scale, e.g., if the scoring key correct response was "strongly agree." "agree" was counted as correct also). Eleven subjects improved their performance after "instruction," but the performance of nine subjects declined from pre- to post-test. It is clear that some subjects benefited from instruction, for example, Subject 20 (see Fig. 10) who improved from 25% correct on pre-test to 73% correct on the posttest, and Subject 17, who improved from 33% correct to 67% correct. But, on the average, subjects did not improve at all in their understanding after directed challenges to their faulty beliefs.

Fig. 10 about here
(pre-post results-inst.)

Subjects' performance on pre- and post-tests of the instructional study was analyzed in yet another way. On a four point scale (strongly disagree, disagree, agree, strongly agree) as was used in the instructional study, one can assign a number to the rating categories (1=strongly disagree, 2=disagree, 3=agree, 4=strongly agree) and compute a deviation between a subject's rating and the correct rating according to the scoring key (e.g., if the subject assigns a 4, "strongly agree." and the correct answer is 2, "disagree," the deviation is two). (Note, a problem with this particular deviation method is that it treats the difference between, say, a "strongly agree" and an "agree" as the same as between, say, an "agree" and a "disagree." This limitation is recognized, but the results, taken as a whole, seem quite clear, despite this limitation). Figure 11 shows such average deviation scores for the pre- and post-test scores for the instructional study being discussed. The mean (absolute value) deviation on the Pre-test was 1.54 and on the Post-test was 1.45. These means are nearly identical and are not different statistically. Note also that, given the scale that was used, a mean deviation of about 1.5 reflects rather poor performances by subjects overall.

Fig. 11-A about here
(Pre-, post-test means, instruction)

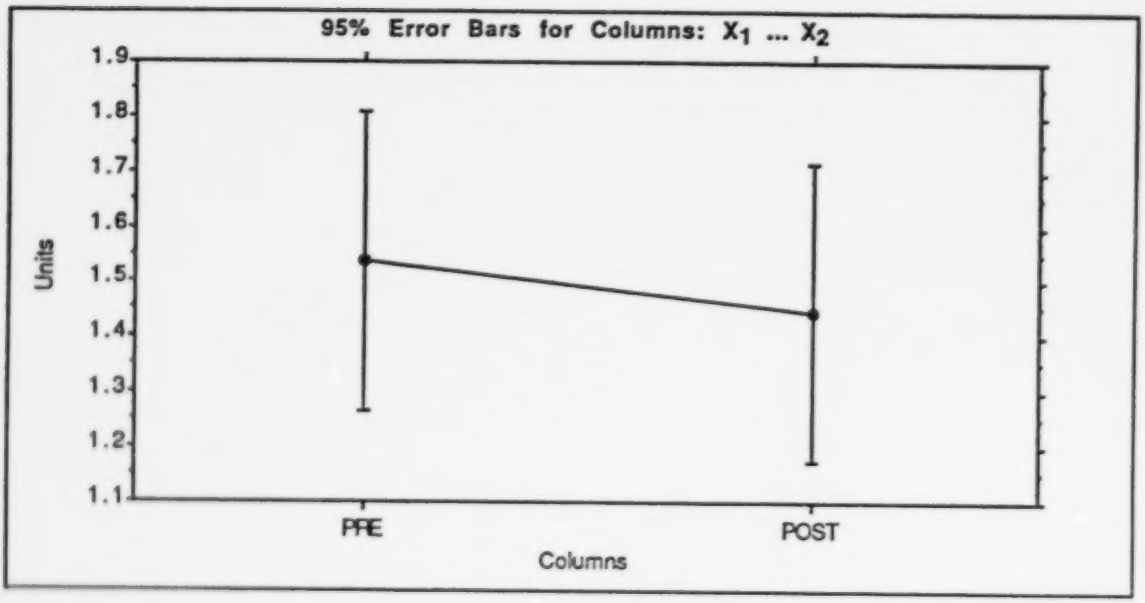
Figure 11-B gives a schematic showing one subject's performance over the entire 75 items of the instructional/challenge study. The subject answered 3/12 (25%) items correctly on the pre-test. After answering only 14/51 (27%) items correctly on the instructional/challenge parts of the procedure, the subject responded correctly to 1/12 (8%) items on the post-test. In can be concluded that the subject did not respond positively to the challenges to his beliefs provided buy the instruction, and post-test performance was not improved at all over the pre-test.

Fig. 11-B about here
(Pre-, post-test, indiv S, instruction)

	SUBJECT	%CORRECT-PRE	%CORRECT-POST
1	S1*	41.6	50.0
2	S2	58.3	50.0
3	S3*	50.0	75.0
4	S4*	25.0	41.6
5	S5	25.0	8.3
6	S6*	25.0	58.3
7	S7	50.0	33.3
8	S8	50.0	41.6
9	S9	58.3	41.6
10	S10	66.6	58.3
11	S11*	16.6	58.3
12	S12	72.7	58.3
13	S13	25.0	25.0
14	S14*	33.3	50.0
15	S15*	50.0	58.3
16	S16	50.0	50.0
17	S17*	33.3	66.6
18	S18*	41.6	58.3
19	S19*	25.0	45.4
20	S20*	25.0	72.7

Challenge Study

Fig. 10



$\bar{x}$ = 1.54 $\bar{x}$ = 1.45

Fig. 11-A

R = right
W = wrong

Trace of one subject thru whole instruction study.

Fig. 11-B

In general, subjects did not seem to change their mostly erroneous beliefs about the role that vascular compliance plays in opposition to blood flow (the Compliance/Resistance misconception) as the result of challenges provided by accurate statements at odds with this misconception.

Other analyses to be discussed, aimed primarily at the conceptual stability construct of Constancy (longevity) with respect to the Compliance/Resistance misconception, will further bolster the claim that this misconception is robust in the face of conceptual challenge. The Compliance/Resistance misconception seems, in addition to being Pervasively held, to be also Robustly held by learners of the pertinent subject matter.

Constancy of the Misconception

Constancy refers to the steadiness of a conceptual belief (across time). Two subjects (second year medical students, referred to as subjects B and K) participated in both the agree-disagree study and instructional study, separated by a period of about seven months. Recall that the pre- and post-tests of the instructional study were composed of items from the agree-disagree study. Hence, subjects who participated in both kinds of studies, over a period of months, can shed light on both the constancy of the misconception and also, because the *Post-test* (after instruction) for the instructional study included some items that were included in the agree-disagree study, can provide a further measure of the robustness of the misconception and its components to instructional challenge.

Figures 12 and 13 show the performance of subjects B and K on test items that they encountered in both the degree/disagree study and the *pre-test* of the instructional studies. These results are an indication of pure constancy of the conceptual belief, since the items were addressed over a period of months but with no instructional challenge (none experimentally, at least--subjects, of course, experienced relevant instruction in the classroom) at either time. The generally poor performances (see Figs. 12, 13) of the subjects demonstrate their belief in components of the Compliance/Resistance misconception. In addition, over the course of seven months, the responses of subjects B and K changed little, if at all. On nine items, subject B changed one answer, from incorrect to correct, and Subject K changed three answers, two from correct to incorrect and one from incorrect to correct. On *post-test* items in common with agree/disagree items, both subjects again demonstrated poor performance (see Figs. 14, 15), and little change from seven months before. Subject B changed responses over this time to two of ten items, one from correct to incorrect and one from incorrect to correct. Subject K changed response to one item, from correct to incorrect.

Figs. 12, 13 about here
(agree/dis inst. pre items in common)

Figs. 14, 15 about here
(agree/dis inst. post items in common)

At least for these two subjects for which the pertinent evidence is available, it is clear that neither intervening time nor the instructional intervention that was provided accomplished any change to the subjects' faulty beliefs about the role that vascular compliance plays in opposition to blood flow (the Compliance/Resistance misconception). For these subjects, the misconception displayed a high degree of Constancy.

KNOWLEDGE SHIELDS FOR FENDING OFF CONCEPTUAL CHANGE

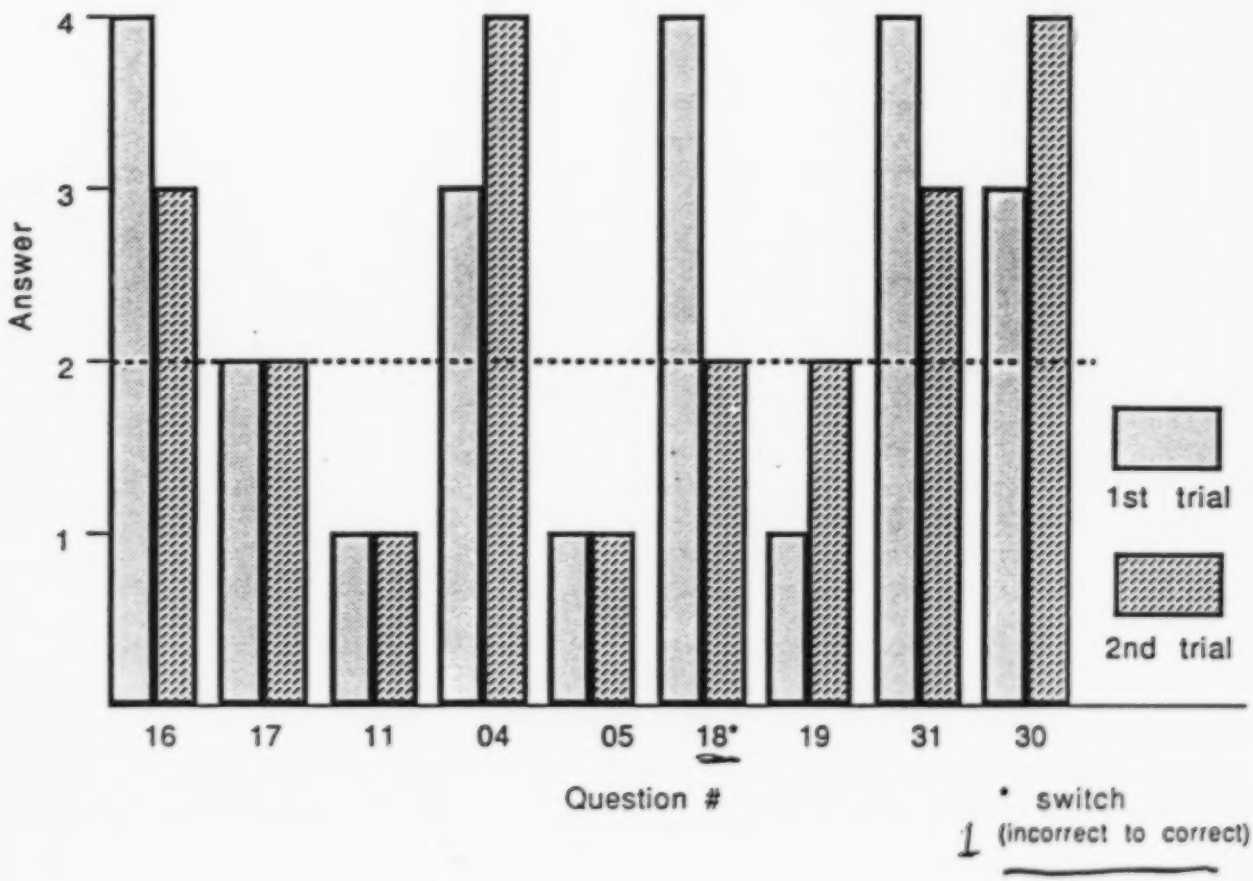
The instructional study was not able to change subjects' faulty beliefs. It did, however, provide a distinct opportunity to investigate what subjects' would do when they were confronted with information (the instructional propositions--see section on the Nature of the Relevant Studies) contrary to what they already believed. In fact, when subjects were confronted with correct "instructional" propositions, they engaged a wide variety of mental maneuvers to help them avoid having to change their minds. We have chosen to call these Knowledge Shields. The Knowledge Shields can be seen to resemble mental operations for handling anomalous information proposed by Chinn & Brewer, 1993, but the Knowledge Shields are more extensive and more detailed. Particular knowledge shields subjects employed in the instructional study are listed in Figure 16.

Fig. 16 about here
(knowl. shields list)

For example, a subject employing the Demean Effect shield acknowledges that what is being proposed (that is discrepant with current belief) might be correct, but dismisses its import by claiming that the implications of its being true are negligible--"That may be true, but it is no big deal." Figure 17 gives a subject's response to a correct proposition that demonstrates Demean Effect. The proposition presented to the subject asserts correctly that during the ascending phase of a pressure pulse some blood must flow into the expansion of the vessel itself and is not flowing downstream through a then wider vessel. This is a challenge to one of the components of the Compliance/Resistance misconception. The subject asserts that such flow may happen, but then wrongly asserts that "it's not a big part of it."

Fig. 17 about here
(demean effect e.g.)

Subject B- Free view/comparison
AD

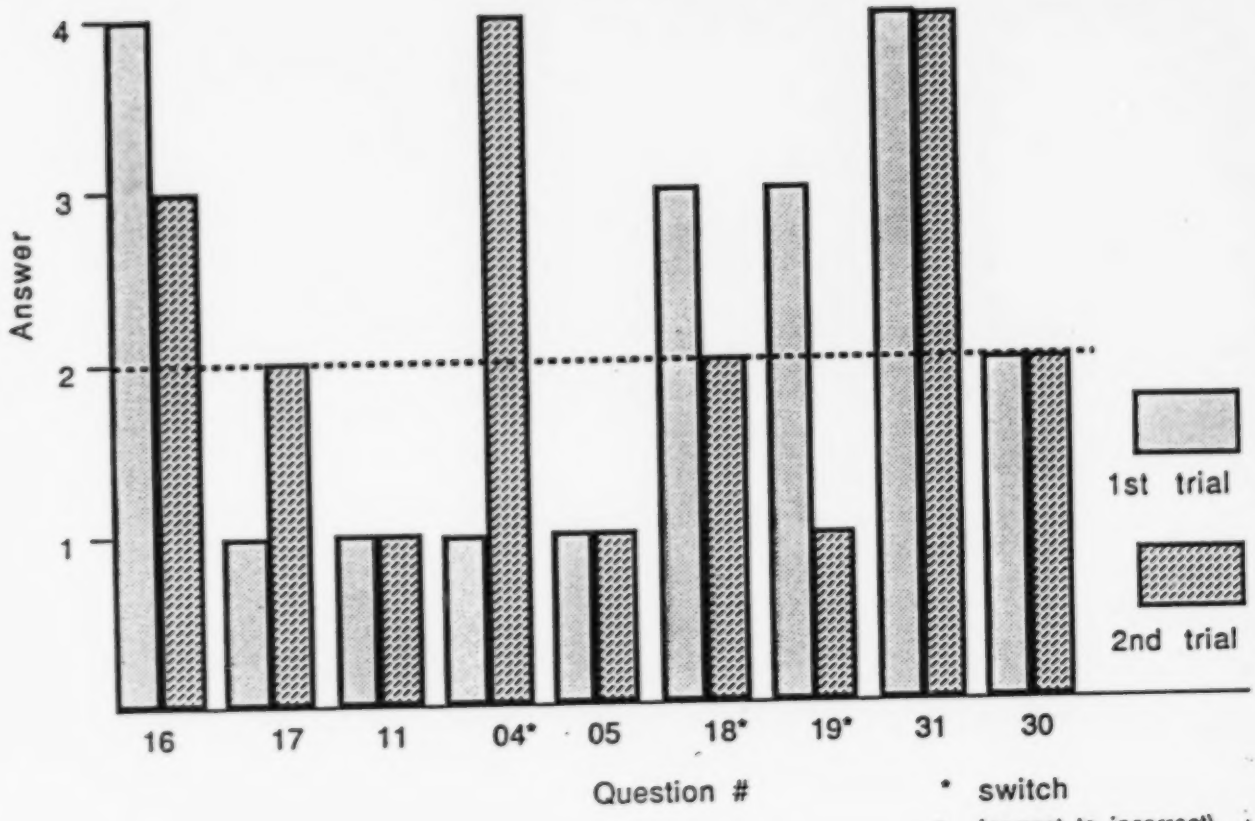


1

1st trial: 1/9 correct (11%)
2nd trial: 2/9 correct (22%)

Fig. 12

Subject K- Free view comparison

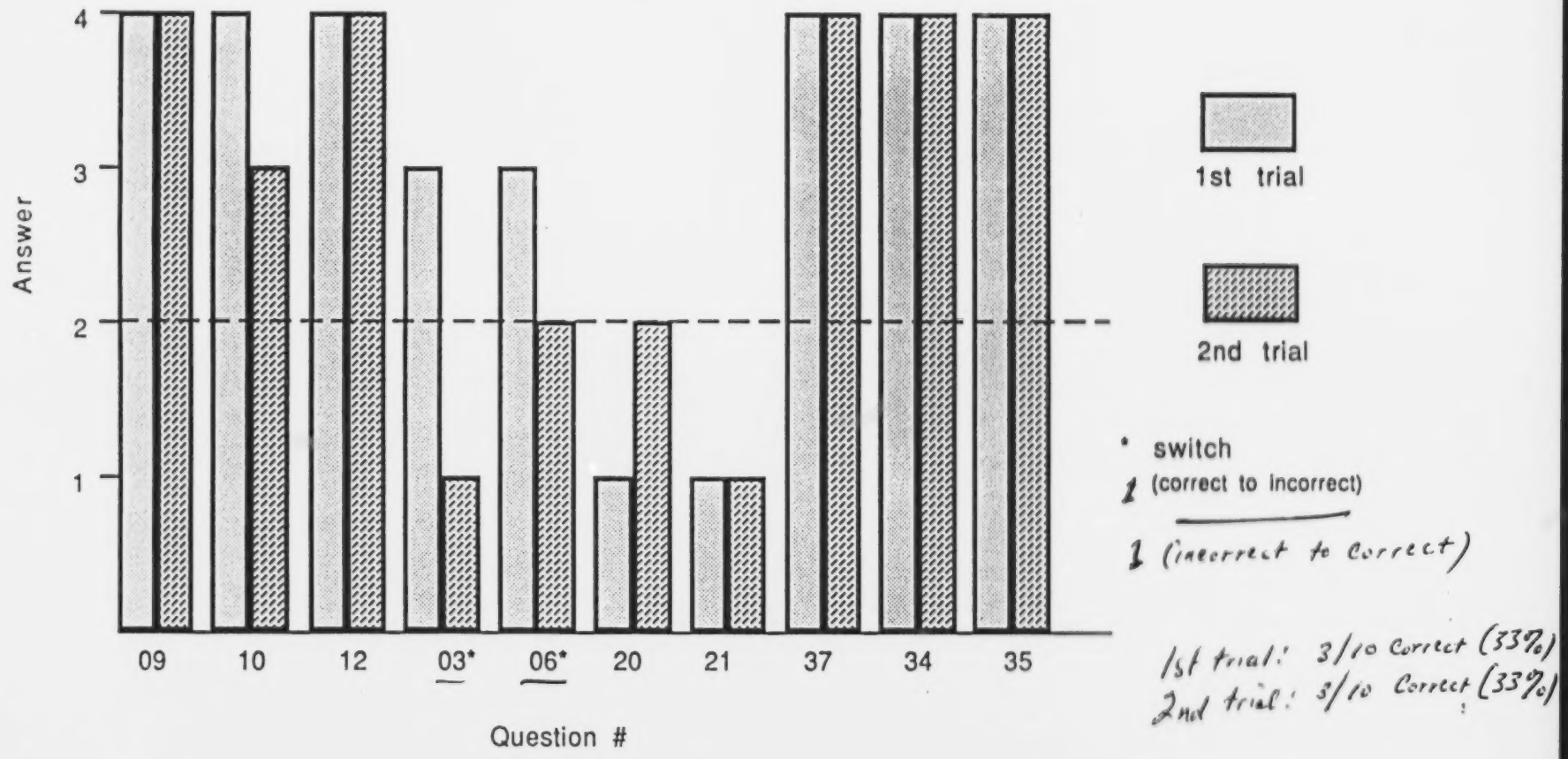


* switch
2 (correct to incorrect)
1 (incorrect to correct)

1st trial: 2/9 correct (22%
2nd trial: 1/9 correct (11%

Fig. 13

Subject B - Post-view comparison

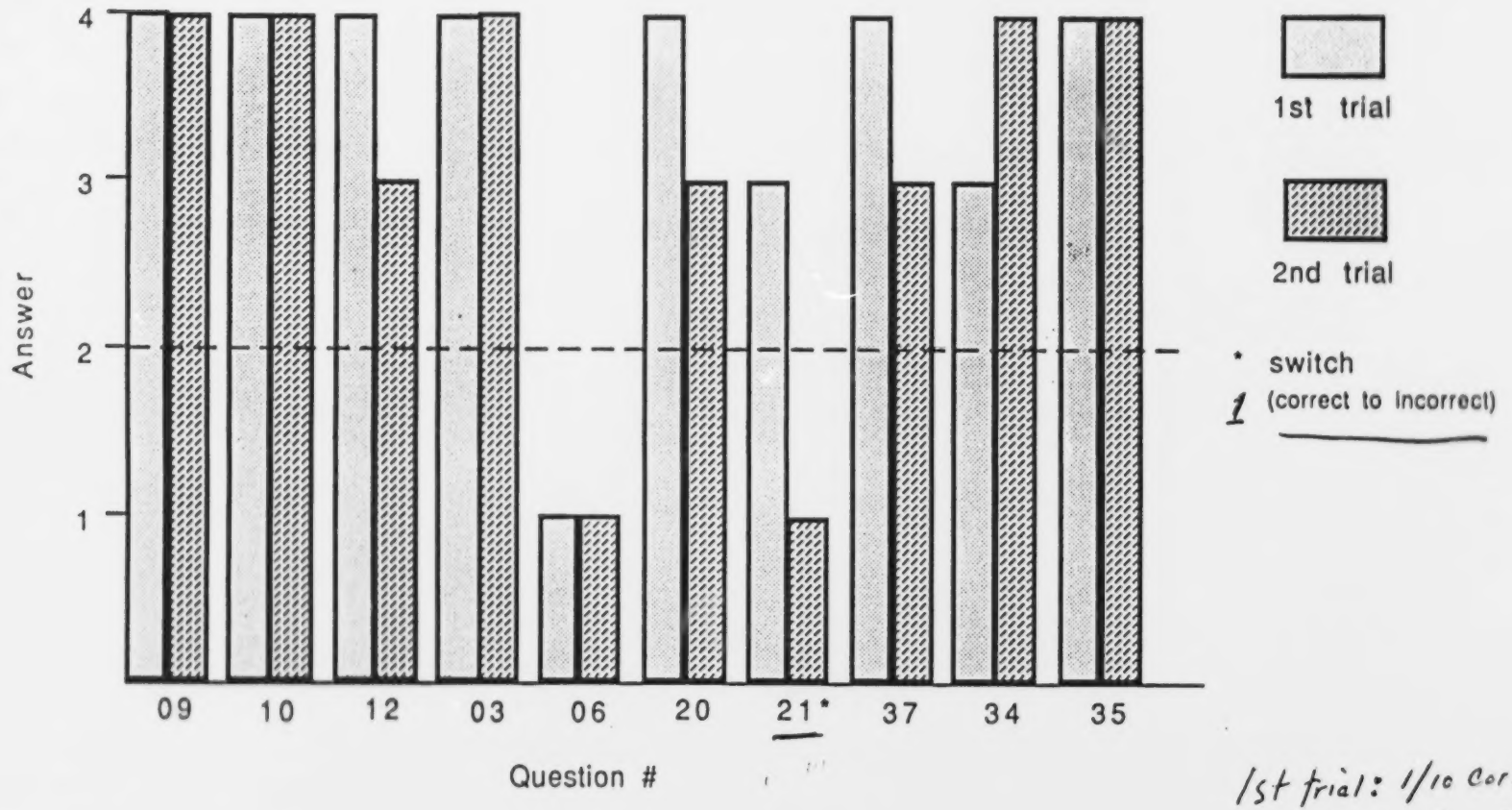


55

56

Fig. 14

Subject K - Post-view comparison



1st trial: 1/10 correct (10%)
2nd trial: 0/10 correct (0%)

Fig. 15

"KNOWLEDGE SHIELDS"
REACTIONS TO TRUE, BUT DISCREPANT INFORMATION:

1(IS) ILLEGITIMATE SUBSUMPTION
: makes new material special case of old. usually agreeing with something we would not expect because subject has way to account for it with bad model.
(Note: variants based on
a) Similarity bias
b) Extension of attributes
c) Reduction to analogy

1a) (PLS) PARTLY LEGITIMATE SUBSUMPTION
: Old knowledge accounts in part for right information. E.G., Knows that resistance and compliance might play different role, but lacks idea of how-- hence can't doesn't change mind.

2) (AU) ARGUMENT FROM AUTHORITY
: new material wrong because Dr. x told me different

3) (DEM) DEMEAN EFFECT
: that might be right but it's insignificant

4) (AA) ADD APPENDAGE
: that might be right, but it's just an add-on to what I believe (when it actually controverts it)

5) (ANAL) RESORT TO BAD ANALOGY
:that (thing about the heart)can't be right because of something I know (but doesn't know right) about the lungs

6) (DE) DECOUPLING OF EFFECTS
: causally related processes/ things are treated as separate. Compliance affects how difficult it is for blood to flow into buldging, but not how difficult to flow out.

6a) (CC) CORRELATION AS CAUSATION.
:blood slipping over itself doesn't cause resistance because radius, viscosity, and length do.

Fig. 16

6b) (ACR) ARGUMENT FROM FAULTY CAUSAL REASONING.
: Agrees/disagrees because of cooked up causal argument that is flawed.

7 (ISE) IGNORING OF SECONDARY EFFECTS
: rebound of vessel doesn't require energy, only expansion does

8) (AE) ARGUMENT FROM EXTREMES (a variety of discreteness bias--e.g., the phenomenon does not exist between the extremes in the example below)
:Yes, increasing compliance can increase opposition, but only when it gets so flacid that blood just stagnates there.

8a) (ASC) ARGUMENT FROM SPECIAL CASE
: It could be true if special boundary conditions hold. (Like AE but just specified conditions rather than extreme ones. E.g., compliant and stiff vessel could have same average radius if different sizes to start with.

9) (CI) COUNTERINTUITION
:Just seems like that CAN'T be right

10) (RADD) (false) REDUCTIO-AD ABSURDUM
:This new thing implies a consequence that conflicts with this other thing that I KNOW is right (where it either doesn't really imply that or the thing they think is right is actually wrong, etc.
(e.g., if last layer of blood were actually stationary, some blood cells would be there for life)

11) (TR) THEORETICAL-REALITY DICHOTOMY
: That may be true in theory, but it isn't like that in reality (e.g., that blood is stationary at the blood--vessel-wall interface).

Fig. 16 (con't)

12) (EXT) EXTIRPATION OF EFFECTS
:increasing heart rate will keep the vessel size relatively more expanded because it doesn't have time to close down between beats (the more compliant the vessel, the more the radius gain from rate will be).
(Decouples from starling/guyton, at least. If true, would lead to explosion!)

13) (FA) FALLACIOUS ALTERNATIVE
:Disagrees because has fallacious alternative explanation. e.g., Stiff vessel sets lower bound on how far compliant vessel could recoil.
Compliant vessel could never recoil to a smaller diameter than the stiffer one.

14) (PKC) PRIOR KNOWLEDGE CLASH
:that is simply incongruent with what I know to be true. (like others, but has simple notion of "I know better")

15) (IC) IMPERTINENT COMPLEXIFICATION.
"Yeh, but there's more to it than that."

16) (AEQ) ARGUMENT FROM EQUATION/FORMALISM
:that s not right because of this equation I know (inappropriate equation, erroneous application, etc. Pressure eq. heart rate x resistance., etc.

17) (ARD). ARGUMENT FROM REDUCED DIMENSIONS.
: Argues using only one or few ot the pertinent dimensions of a situation. That's not right because P = RxF.

18) (RAP) RESTRICTED APPLICABILITY OF PRINCIPLE.
:that might be right, but it only applies in special circumstances. Increased stiffness will only cause increased opposition in veins, say.

19) (ASR) ARGUMENT FROM STATIC REPRESENTATION OF DYNAMIC.
:Argument that assumes rate eq. volume, etc.

20) (ASE) ARGUMENT FROM SALIENT EXAMPLE.
: that can't be true because of this example I know. Not used so much as analogy, but example of the issue under contention (but misplaced).
Decreasing compliance always leads to greater opposition, because of atherosclerosis etc.

Fig. 16 (con't)

21) (AUA). ARGUMENT FROM UNRELATED ALTERNATIVE.
: that's not right because this other thing I know is. Heart rate can't be related to contribution of stiffness because sympathetics determine stiffness...

Fig. 16 (con't).

50b. As a vessel expands during the ascending phase of a pulse, this does not mean that all of the blood in the expanded vessel simply flows downstream through a now larger vessel, since some of it, for instance, flows into the expansion of the vessel itself.

(long pause) "Um, I'm gonna agree. It sounds, it makes sense that some of it would flow into the expansion of the vessel, but I'm sure it's not a big part of it. My confidence is 50%.

KNOWLEDGE SHIELDS USED:

DEM - Demean effect

Fig. 17

The use of other shields is demonstrated in Figures 18 and 19. In Figure 18, a subject dismisses a fact about vessels in the cardiovascular system by importing a (false) analogy about the pulmonary vascular system--Argument from Analogy (see Fig. 16). In Figure 19, a subject agrees with a proposition we would have expected him to disagree with--that opposition to blood flow is affected by heart rate. However the subject manages to agree only by employing two knowledge shields that protect the subject from the need for an actual change of mind--Argument from (faulty) Causal Reasoning and Extirpation (excision of something from its context--ignoring effects of context). In particular, blood does not flow backward during a beat (Faulty Causal Reasoning), and one could only believe that it might by viewing things locally and ignoring the full, system-wide environment of any vessel: that is, by ignoring the fact that the pressure gradient necessary for any forward or backward flow (as opposed to flow into the walls) is always in the down stream direction of the atria of the heart. Flow is always downstream whether the vessel is expanding or contracting (there is actually a brief exception to this in the region of the aorta, but this is irrelevant to what this subject is displaying).

Figs. 18,19 about here
(anal and extir shields)

As a final example of the use of knowledge shields, consider the subject statement included in Figure 20. Again, this subject agrees with a proposition he would not be expected to agree with, but he does so because he engages shields that avoid the need for any change to his fundamental misunderstanding. The presented proposition is an appropriate description of the causal basis for resistance in blood flow, involving static liquid (blood) at the interface with the vessel walls and the need to overcome molecular bonds within the remaining blood itself to yield flow. This is in conflict with component misconception #6 of the Compliance/Resistance misconception (Fig. 3), a component in which it is assumed that resistive forces to blood result from some kind of frictional interaction between the moving blood and the vessel wall surface. First, in the faulty analysis, the subject leaves some room open for some frictional effect by viewing the outer layer of blood as *relatively* stationary, not stationary (Demean Effect), and then further bolsters the need for some motion there by engaging a False Reductio Adabsurdum--that if the outer layer did not move some blood cells "would stay in the body forever." The latter is a kind of Static Representation of the Dynamic life of a cell--that it gets created and survives in its same form forever.

Fig. 20 about here
(false reductio e.g.)

Figure 21 gives a rough accounting of the Knowledge Shields used by three subjects during the instructional study. (Refinement of the Knowledge Shields themselves and the coding of their use by subjects is still ongoing--minor details will probably change but not the basic phenomena). The Figure shows prevalent and varied use of these shields by subjects, reflecting what seems like a dedicated effort to keep from changing beliefs that are already held.

#11. In the pulsing cardiovascular system, two vessel segments which would have the same diameter at constant pressure (not pulsing) will both have the same average diameter in the pulsing system even though one is highly compliant (stretchy) and the other is very stiff.

"Um, well I would disagree because it's kind of like with the pulmonic valve and the aorta, the pulmonary system is more compliant so the diameter's bigger when it's bulging? If that make sense. My confidence rating is 70%."

ANAL: Arg. from (Bad) Analogy

Fig. 18

#69/54b. In the pulsing cardiovascular system some of the energy produced by the heart is used up in making blood flow into and out of the expansion of vessel walls. Hence, factors associated with flow into and out of the vessel walls such as wall stiffness and heart rate contribute to opposition to blood flow.

"And I agree with that um, because when blood goes into the expanded area and then that expanded area contracts, the blood's gonna go both forwards and backwards and this is gonna create opposition to other blood coming in, and I would say I'm _____ confident."

KNOWLEDGE SHIELDS USED:

(1) ACR: Argument from causal reasoning (back flow)

(2) IS: Illegitimate Subsumption - use wrong model to account for effect

(3) EXT: Extirpation - Ignores system (pressure downstream)

Fig. 19

#30M The resistance to the flow of blood in a vessel ultimately results , in large part, from the blood in contact with the vessel wall being stationary and the blood not in contact with the wall being in motion and having to slip over itself.

Yeah, I agree, in fact I strongly agree...the blood that actually contacts the vessel wall is relatively stationary ah, of course, nothing is totally stationary, although as you (would) find that ah, some red blood cell would stay in your body forever, but it's relatively stationary and the, the center level or layer flows much faster than the outer level and slips over itself and glides. So I strongly agree, my confidence rating is 80%.

Knowledge Shields Used:

1) RADD: False Reductio Adabsurdum
2) ASR: Argument from Static Rep of Dynamic
3) DEM: Demean Effect

Fig. 20

Fig. 21 about here
(k-shields used-3s's)

SUMMARY AND CONCLUSIONS

In this section, a summary of what has been presented in the report is given first. This is followed by some conclusions and implications.

Background for the research was presented first. This included, most importantly, a discussion of the focus of our prior research on important and difficult concepts of a subject matter; the description of a "calculus" for capturing the nature and structure of the many misconceptions that students acquire about these concepts; and presentation and discussion of some prevalent ways of thinking, Reductive Biases, that contribute to the acquisition of the faulty understandings.

A scheme, the Conceptual Stability Scheme, was presented for analyzing a concept and its related concepts for potential stability. Such analysis can be used to determine how prone a cluster of concepts is to be misunderstood in learning and for predicting how stable the ensuing misconceptions are likely to be once they are acquired. The Scheme was instantiated for a misconception (the Compliance/Resistance misconception--and a related Resistance-only model of opposition to blood flow) about the cardiovascular system, and in this analysis the misconception was predicted to be highly stable: *pervasive* among learners, *robust* in the face of challenge, and *constant* over time.

A set of studies was presented that confirmed that the misconception that was predicted to be highly stable according to the Conceptual Stability Scheme was, in fact, highly stable. (It should be noted that claims about the predictiveness of the Conceptual Stability Scheme must be tempered despite its apparent success in the reported set of studies. We have not, for instance, tested a misconception the Scheme would predict should be easy to change. In general, much more work remains to be done.) This Compliance/Resistance misconception is widely held (*Pervasive*) among learners of cardiovascular physiology This was confirmed by the results of all the studies presented. It was shown from the results of an "instructional"/challenge study that providing challenges to this erroneous belief had little effect on improving students' understanding (i.e., the misconception is *Robust* in the face of challenge). Finally, subjects (albeit only a couple) who were tested twice, separated by a seven month period, showed virtually no change in performance, suggesting the *Constancy* of the misconception.

Knowing, in advance, how subjects would think, and think incorrectly, about a set of important concepts provided a fine opportunity to examine how the subjects would handle correct information at odds with their erroneous beliefs. These challenges were provided by the challenge items of the instructional study. It was discovered that the students routinely engaged mental maneuvers to rationalize the discrepancies between their own beliefs and the correct information, in ways that enabled them to keep from changing their own faulty models (from "changing their

	KNOWLEDGE SHIELDS	S-2	S-5	S-11	SUM
1	Argument from (faulty) Causal Reasoning (ACR)	11.0	26.0	14.0	51.0
2	Extirpation of Effects (EXT)	3.0	13.0	6.0	22.0
3	Illegitimate Subsumption (IS)	6.0	7.0	7.0	20.0
4	Decoupling of Effects (DE)	6.0	12.0	0	18.0
5	Ignoring Secondary Effects (ISE)	3.0	14.0	0	17.0
6	Argument from Reduced Dimensions (ARD)	0	7.0	6.0	13.0
7	Fallacious Alternative (FA)	3.0	8.0	0	11.0
8	Prior Knowledge Clash (PKC)	4.0	4.0	1.0	9.0
9	Demean Effect (DEM)	4.0	3.0	0	7.0
10	Argument from Special Case (ASC)	7.0	0	0	7.0
11	Argument from Extremes (AE)	5.0	0	0	5.0
12	Argument from Static Rep Of Dynamic (ASR)	0	1.0	4.0	5.0
13	Theory-reality Dichotomy (TR)	5.0	0	0	5.0
14	Argument from (bad) Analogy (ANAL)	3.0	0	1.0	4.0
15	Correlation as Causation (CC)	3.0	0	0	3.0
16	Argument from Unrelated Alternative (AUA)	0	3.0	0	3.0
17	Argument from Authority (AU)	2.0	1.0	0	3.0
18	Add Appendage (AA)	0	1.0	1.0	2.0
19	Impertinent Complexification (IC)	2.0	0	0	2.0
20	Partially Legitimate Subsumption (PLS)	2.0	0	0	2.0
21	Restricted Applicability of Principle (RAP)	1.0	0	0	1.0
22	Argument from Salient Example (ASE)	0	1.0	0	1.0
23	Argument from Equation/Formalism (AEQ)	1.0	0	0	1.0
24	Counterintuition (CI)	1.0	0	0	1.0
25	False Reductio Adabsurdum (RADD)	1.0	0	0	1.0

Fig. 21

minds"). Numerous Knowledge Shields were identified, and some examples of their use by subjects were presented.

The set of studies, taken as a whole, verify that misconceptions can be held pervasively, with a high degree of internal consistency and coherence, and *tenaciously* (see Fig. 22). For example, the results of the instructional/challenge study indicated that the instructional part might as well not have even been there; it had so little effect on improving students' understanding. Furthermore many, and *many different kinds*, of, Knowledge Shields were engaged by students to protect their prior knowledge, and the challenges to their knowledge often made them angry. A testimony to the degree of discomfort the challenges caused some students was the amount of anger and frustration that was elicited within the experimental procedures. For example, Figure 23 gives the reaction of a subject during a part of the instructional procedure in which the appropriate role of compliance in opposition was explained, along with the fact that increases of compliance need not always decrease opposition, and that decreases need not always increase it. As the subject himself said "I *don't want* to think this way!"

Fig. 22 about here
(thoughts)

Fig. 23 about here
(subject yelling)

The results indicate that resistance to change of belief is opportunistic. As has been noted, many different kinds of Shields were used, and in many different places and kinds of circumstances. It is as though the subjects would muster whatever means they could to ward off the potential effects of discrepant information, any time they encountered it. In this sense, the fending off of conceptual change among students seemed more unprincipled and timely than it did calculated and systematic.

This suggests one reason why the emending of misconceptions about complex concepts and subject matter may be especially difficult. In other papers we have proposed a complex and intricate structure for groups of related complex concepts (Coulson et al, 1989; Feltovich et al., 1989). This structure is network-like, with many interlinked components that can bolster each other in diverse and complicated ways, so that, for instance, the effects of a change in one component can be overridden by the conjoint effects of many others. If the application of Knowledge Shields is catch-as-catch can, as our results suggest, then conceptual change should be especially difficult for concepts of the kind we have proposed. This is because in this kind of structure *there are so many places to hide* the effects of discrepant information. For example, there can be no such thing as a *critical challenge* to some key part of the network of misconception because of the multiplicity of influences on belief. This kind of conceptual network provides so many sources of resiliency that some way can be found by the learner to accommodate the implications of a challenge to credibility. Changing belief probably requires a multi-

THOUGHTS

1) TENACITY -

LIKE "INSTRUCTION" WASN'T THERE (ON AVERAGE).

LOTS OF USE OF THE SHIELDS.

SUBJECTS SOMETIMES GET ANGRY (SEE LATER).

2) FENDING OFF CHANGE IS

OPPORTUNISTIC - LOTS OF PLACES

UNPRINCIPLED - PULL OUT ANYTHING YOU CAN.

3) SO MANY, MANY TRAPS, PLACES TO HIDE, COVER, SHIELD.

(in a complex subject matter)

Fig. 22

Reaction to the Good Compliance Description

This is dangerous thinking. No, to my mind I don't want to think this way. No, because I could say, I'd have to then think backwards. I'd have to think, unless I still haven't gotten your point, I would then have to conclude that it's good to have non-compliant vessels...So furthermore, I mean, the whole structure of cardiovascular physiology, the whole framework I use to understand it, is based on, you know, some key points. And this isn't one of them!

Fig. 23.

faceted, systematic affront, a process of dismantling and reconstructing a large part of a belief *system*.

Others have proposed or documented a kind of *inertia* in human belief, a proclivity not to change belief easily (e.g., Abelson, Aronson, McGuire, Newcomb, Rosenberg, & Tannenbaum, 1968; Chinn & Brewer, 1993; Festinger, 1957; Harman, 1986; Sowa, 1984; White, 1983). Structures of knowledge built up over long periods of time, and, presumably, having been shown to have some utility for functioning in the world, should not be abandoned in a fickle way. To some extent, the users of the Knowledge Shields we have identified were being good epistemological "scientists," (even if a bit haphazard), subjecting potential sources of change to strong scrutiny (e.g., checking the implications of the challenging knowledge--Reductio adabsurdum--seeing first if the old model could be modified--Subsumption--rather than abandoned, and so on).

It would be good for any agent that learns, human or machine, to have such tests it can apply to a threat to its existing beliefs. Furthermore, with the development of expertise in an area, one might assume that the ability to apply such tests judiciously and constructively would improve. Perhaps our contribution here has been to start to stock a catalogue of such epistemological "scrutinizers" that are used by (at least *novice*) learning systems--for good or bad. Further development and validation of this catalogue could be useful in teaching humans by elucidating what the instructional process is up against, i.e., the kinds of sources of resistance to change that are likely be employed by the learner. Better understanding of what we have called Knowledge Shields could also be useful in building (and training) intelligent machines that are supposed to change adaptively as the result of experience--for designing, for example, expert systems that are supposed to learn from and benefit from complex interactions in the world.

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